LISA

Beyond Einstein: From the Big Bang to Black Holes

Achieving the Very Low End of the LISA Sensitivity Band

Stephen M. Merkowitz

NASA/GSFC

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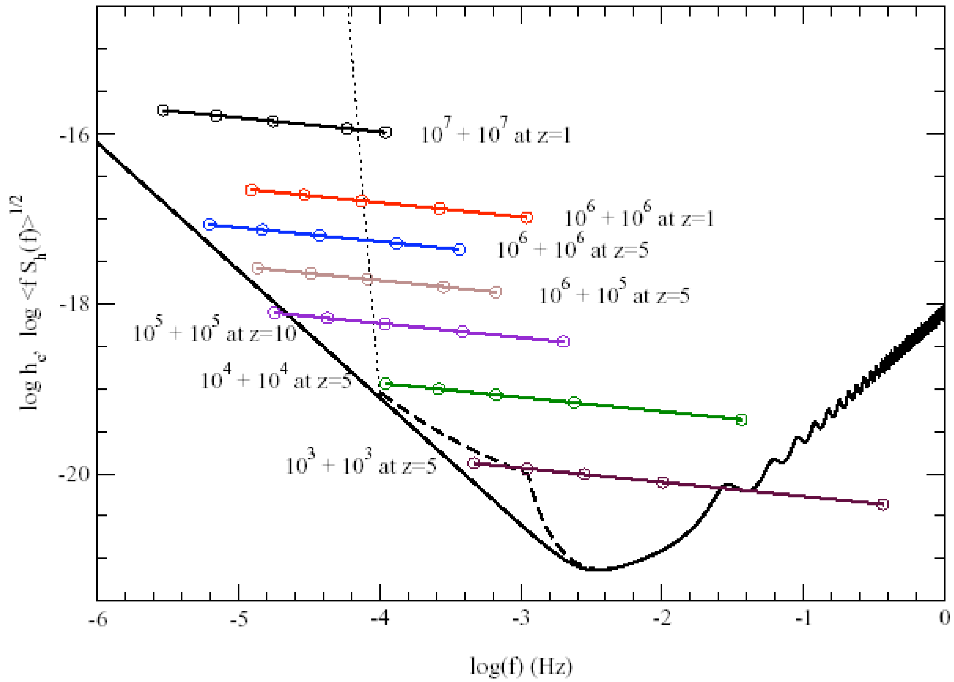
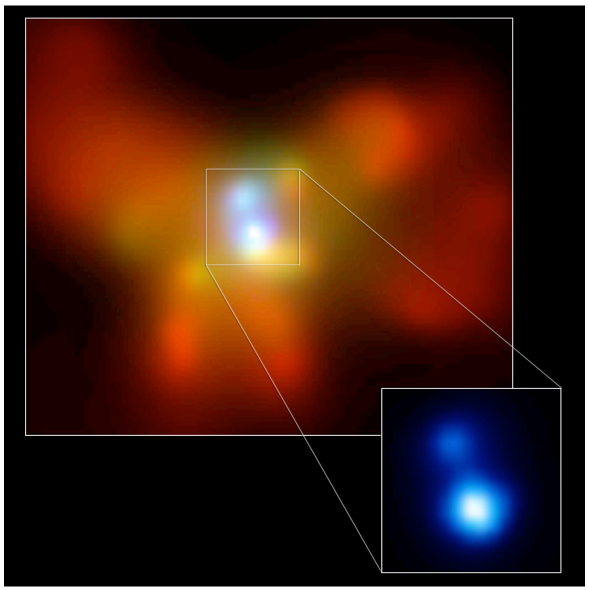
GSFC - JPL

esa

Low Frequency Science

- Massive black holes are believed to be at the center of all galaxies with bulges.
- Typical galaxies are believed to have at least one merger.
- Gravitational waves from final merger are detectable by LISA to high z (~20)
- Expect multiple events per year within LISA sensitivity.
- Observations of such events by LISA:
  - Can be used to map merger history of MBHs (and their host structures) to high z,
  - Provide tests of strong GR dynamics.
- Better low-frequency sensitivity:
  - Better distance resolution,
  - Longer integration time -> better angular resolution,
  - More secure sources.





LISA Frequency Response

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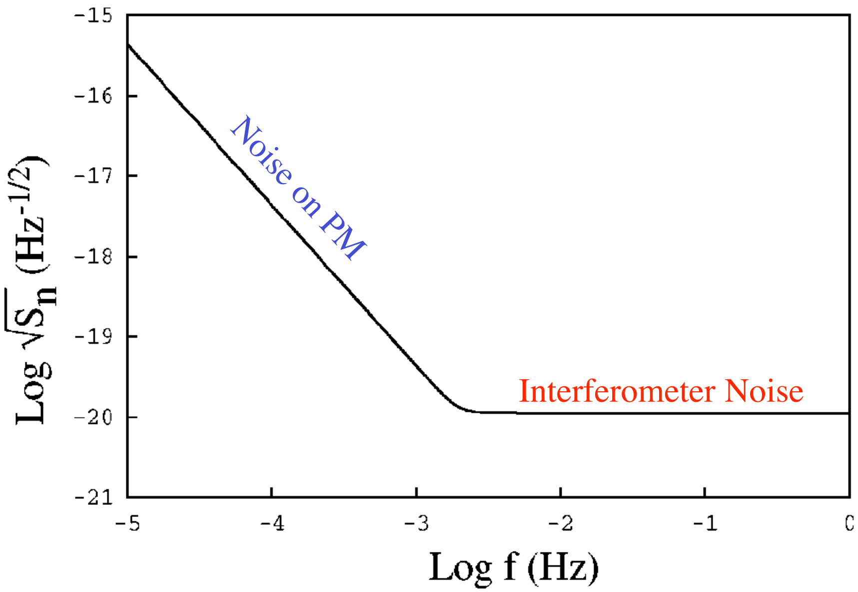
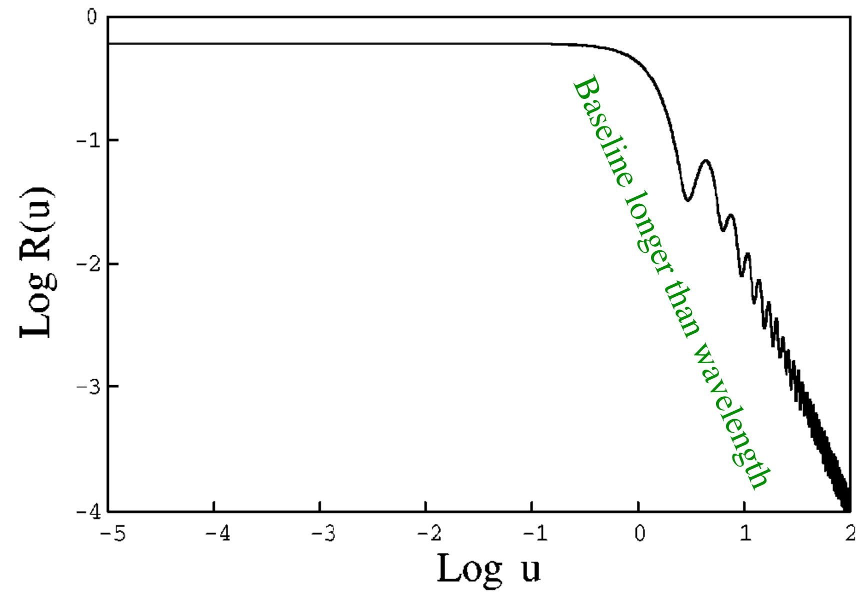
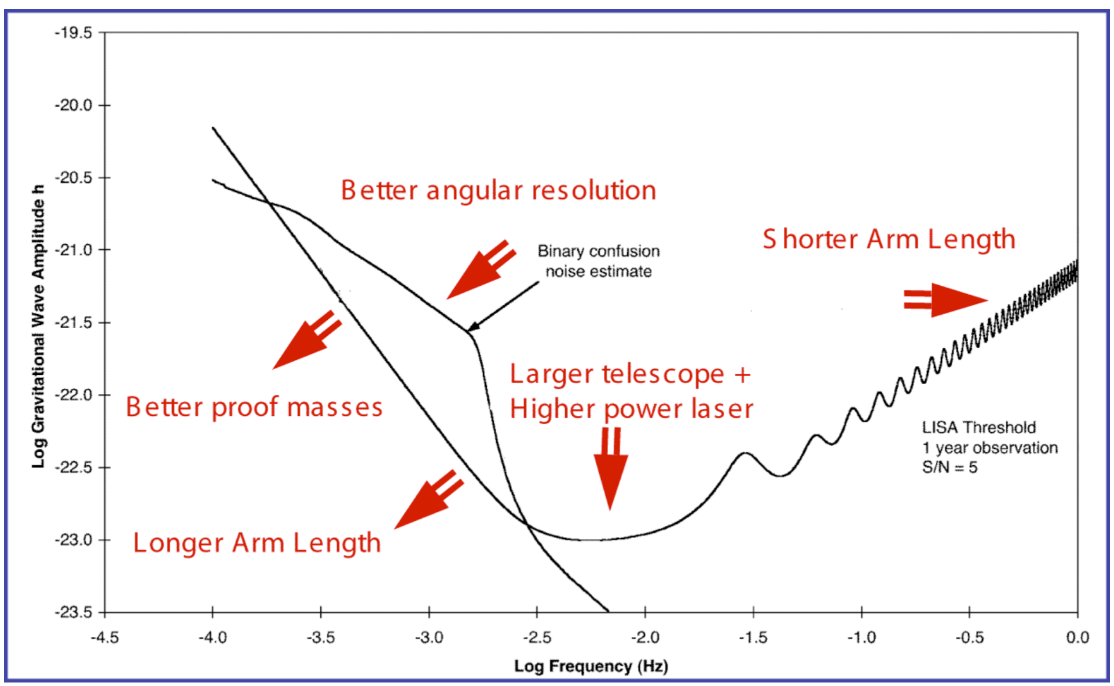
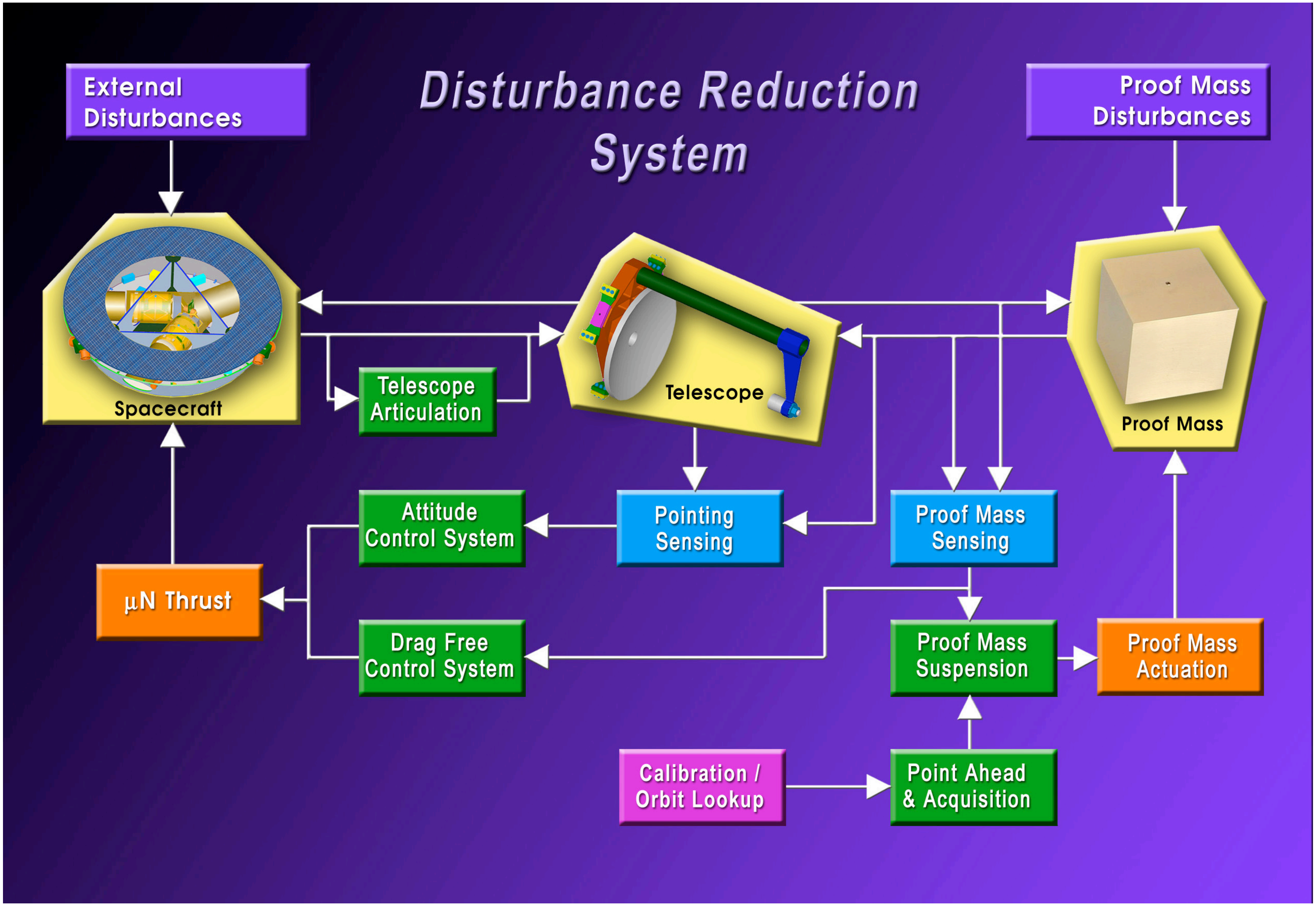




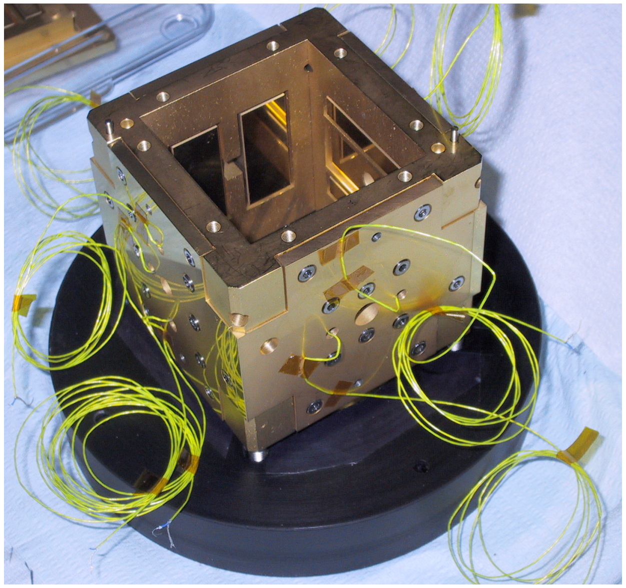


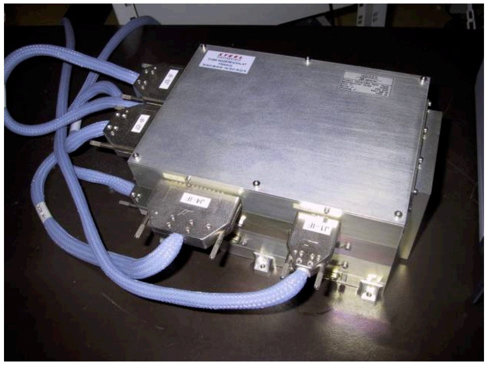
Disturbance Reduction System (DRS)

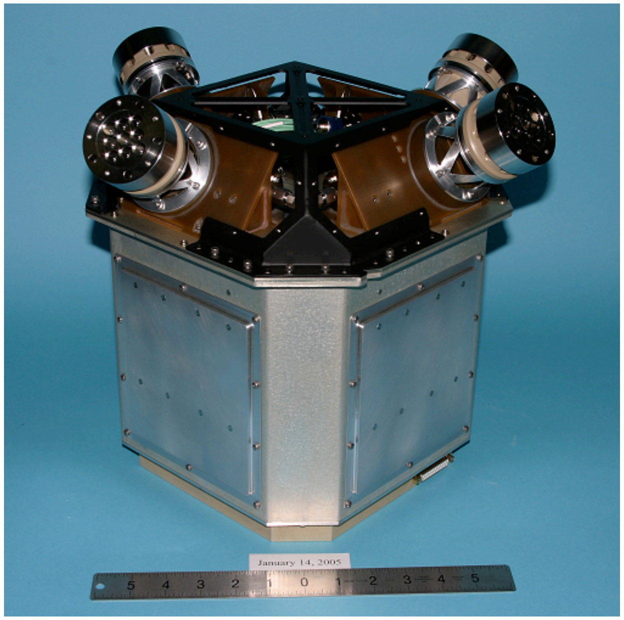


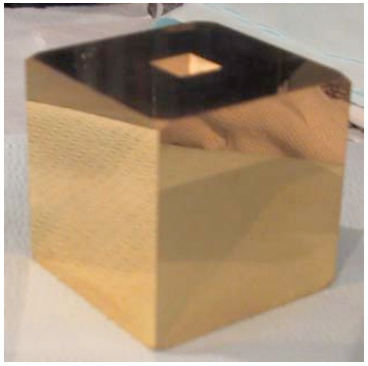
Disturbance Reduction Technology

- Gravitational sensor
  - Two GRS's on each LISA S/C.
  - The LISA GRS will fly on LPF
  - Ground development of Pathfinder GRS complete.
  - GRS EM successfully passed thermal-vac and vibration testing.
- Microthrusters
  - European FEEPs will fly on LPF
  - US electrospray (colloid) thrusters will fly on LPF
- Control System
  - 57 DOFs
  - Drag-free control similar to LISA configuration will be demonstrated on LPF.

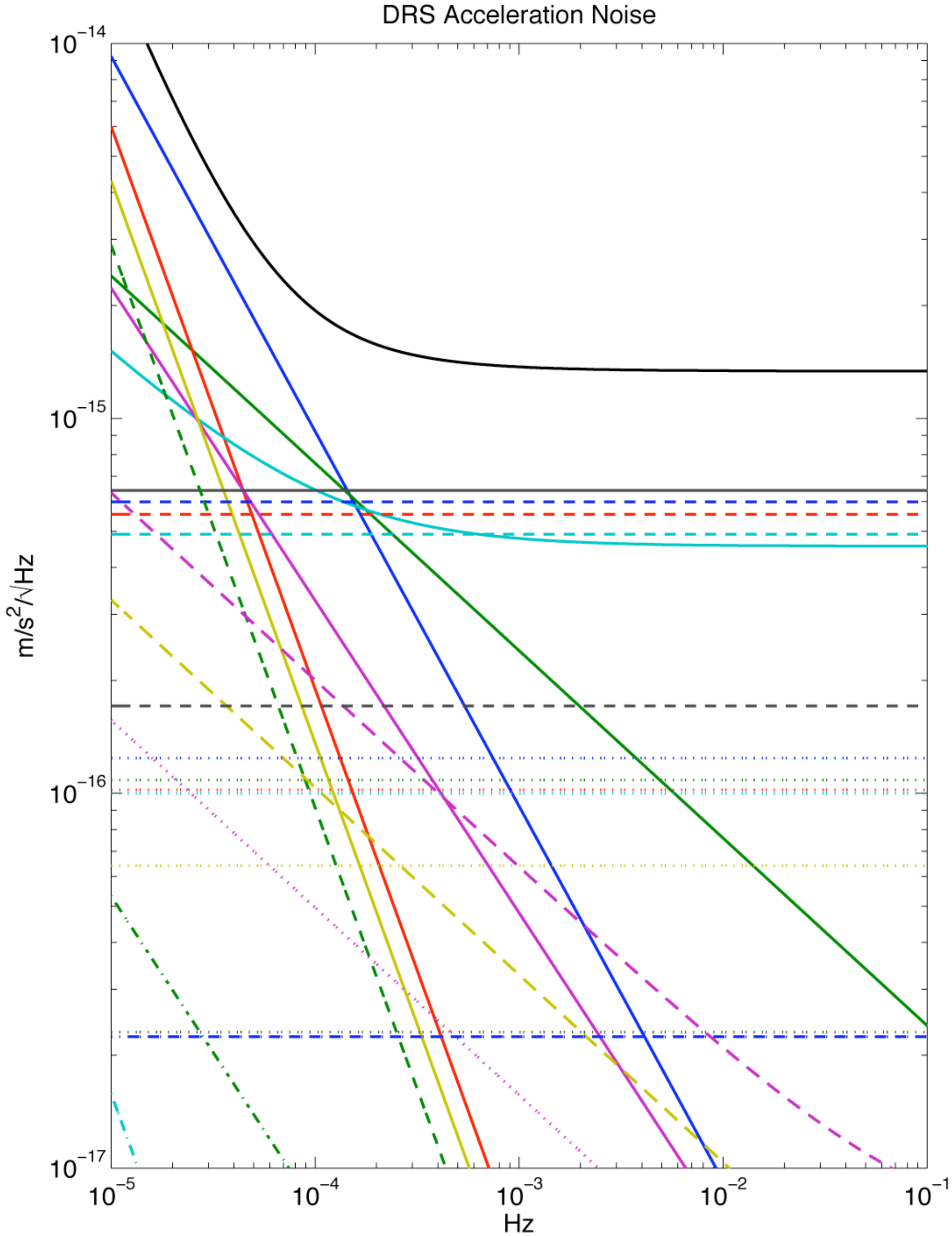






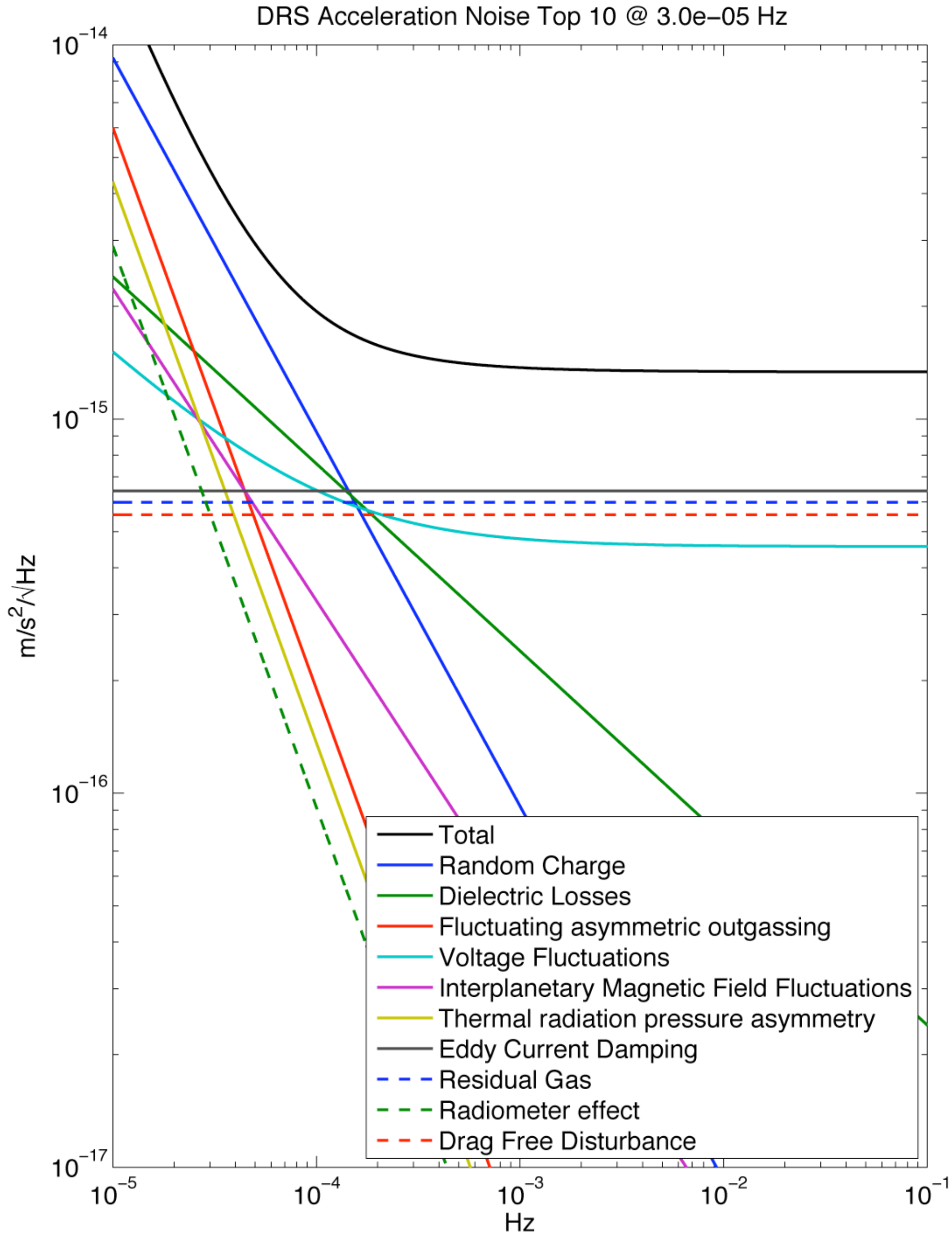


DRS Acceleration Noise Model



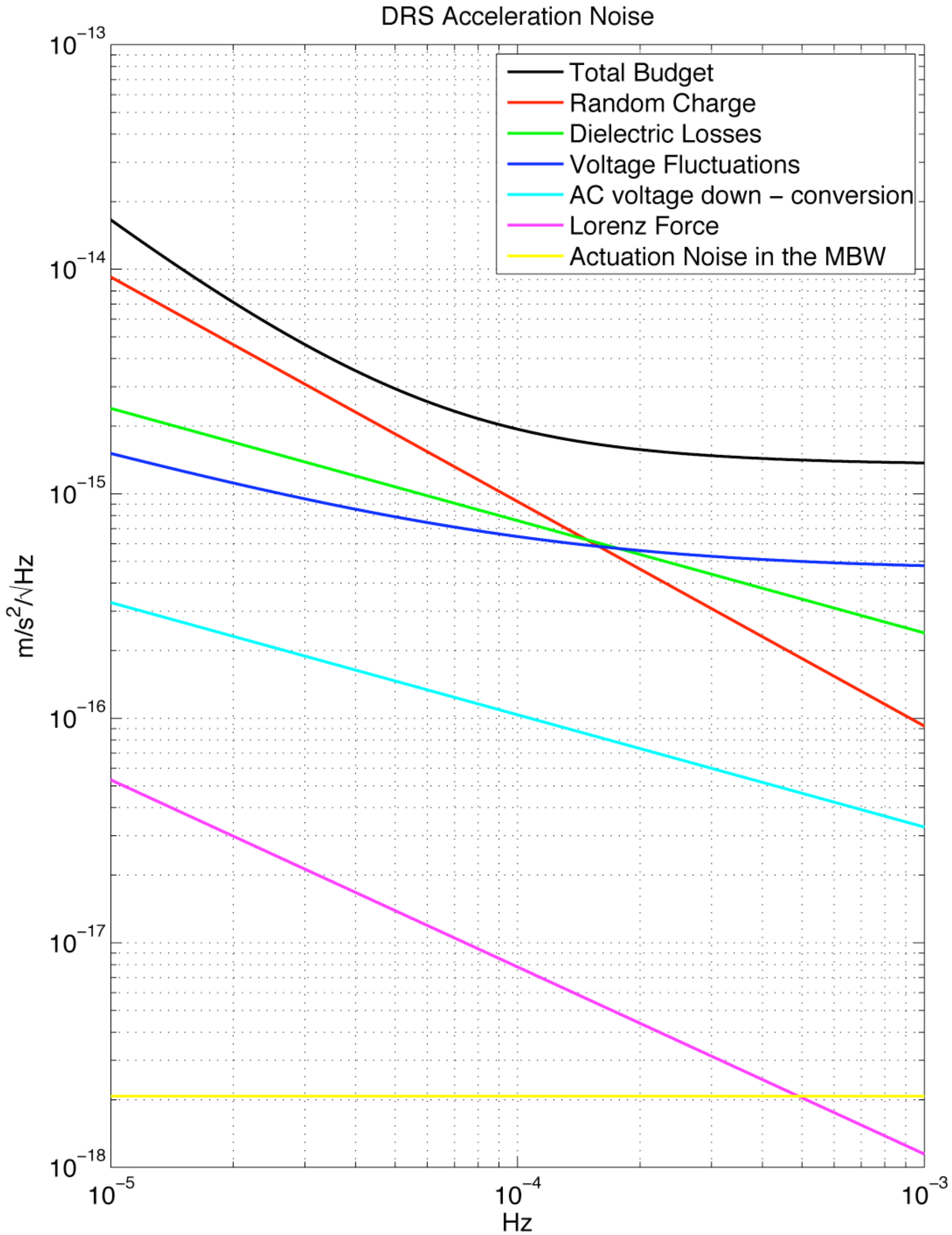
- Current DRS noise model includes:
  - 50 physical effects
    - Steady state PM acceleration
    - Steady state PM torque
    - PM-S/C coupling (stiffness)
    - Direct PM acceleration noise
  - 123 physical parameters
- Available parameter values:
  - Budgeted
  - Current best estimate
  - Goal/optimistic

Top 10 Effects at 0.03 mHz



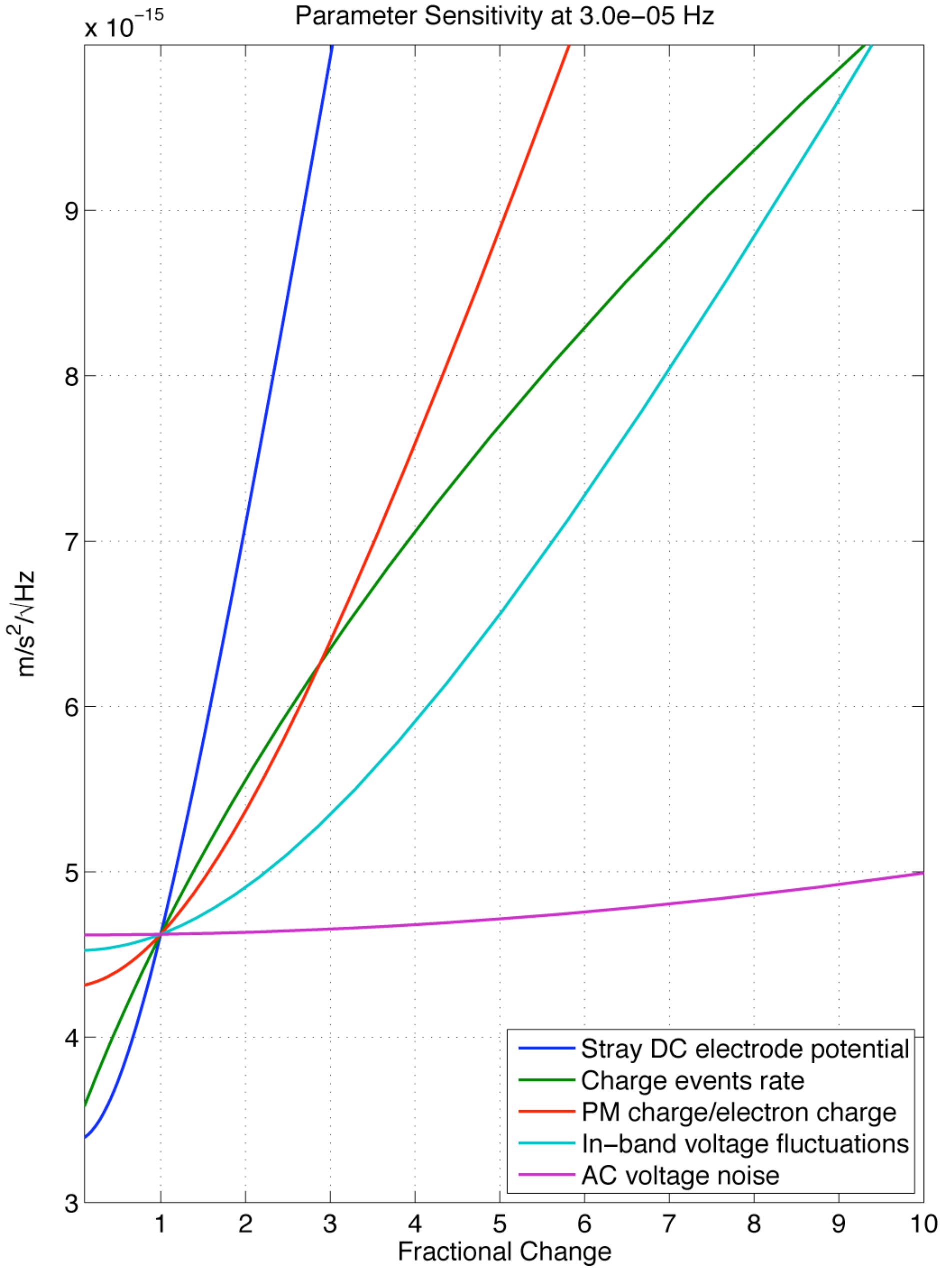
- Charge & voltage effects
- Thermal effects
- Magnetic effects
- Spacecraft to proof mass coupling

Voltage & Charge Effects

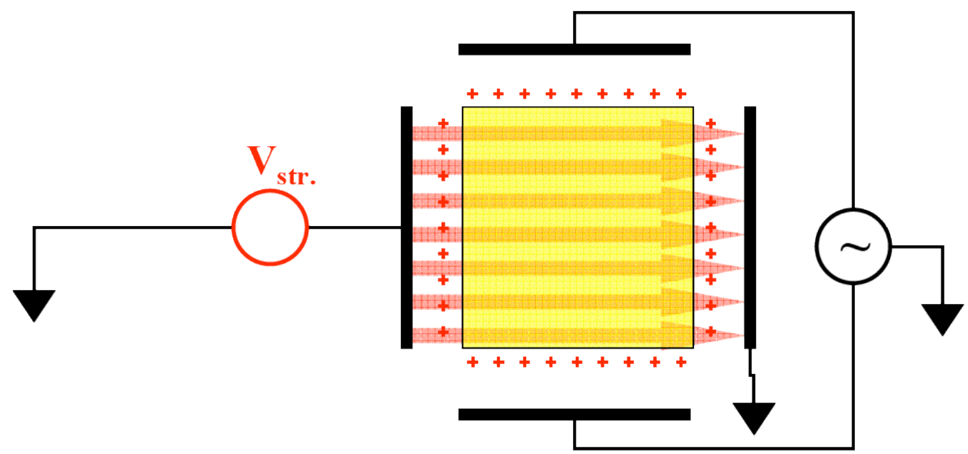


- Random Charge
  - Fluctuating PM charge coupled to DC field.
- Voltage Fluctuations
  - In-band fluctuating stray voltages coupled to PM charge and stray DC field.
- Dielectric Losses
  - Thermal noise from lossy capacitors.
- DC Voltage Stiffness
  - PM electrostatic coupling to S/C motion

Voltage & Charge Parameters

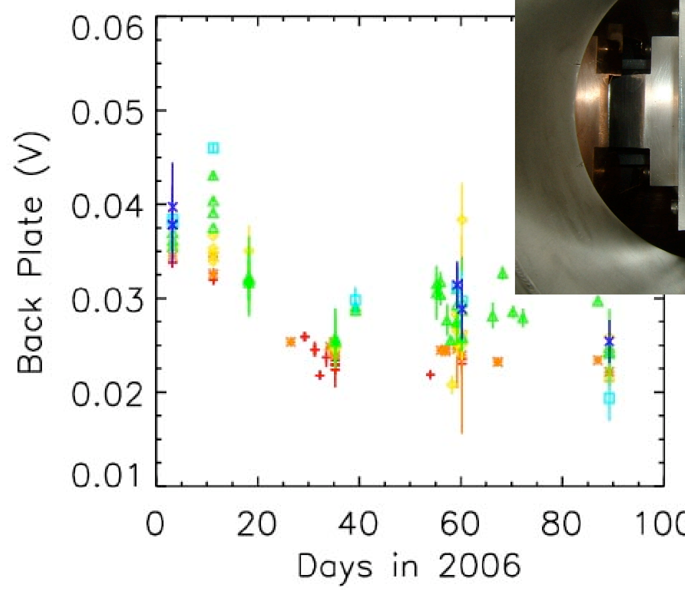


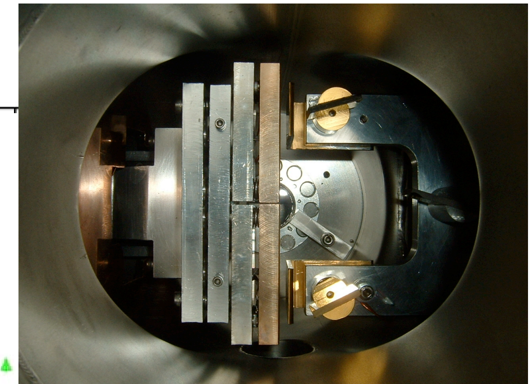
Description	Budget	Units	Sensitivity
Stray DC electrode potential	0.01	V	0.457
Charge events rate	500	1/s	0.222
PM charge/electron charge	$1.0x10^{7}$		0.120
In-band voltage fluctuations	$2.1x10^{-5}$	V/√Hz	0.042
AC voltage noise	$1.8x10^{-7}$	V/√Hz	0.002



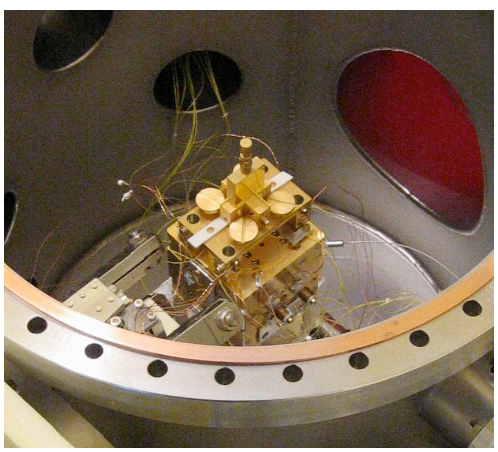
Stray DC Potential

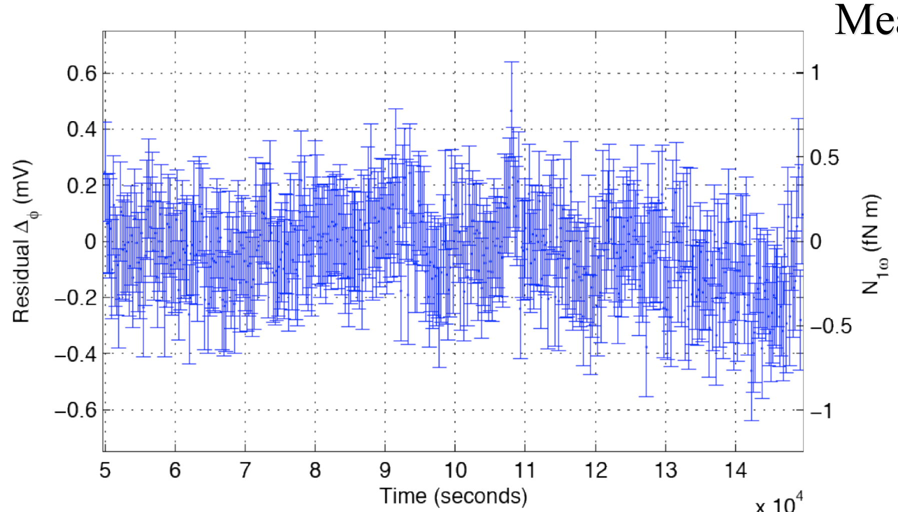
- Spatial average of voltage difference from opposite faces.
- Mostly from ‘large’ patches of spatially varying surface potentials.
- Can be partially compensated by carefully applied electrode voltages.
- ⚓ Measurements at UW confirm stray DC voltage of ~50 mV.
- ⚓ Measurements at Trento demonstrate compensation to ~0.5 mV.





UW Small Force Measurements

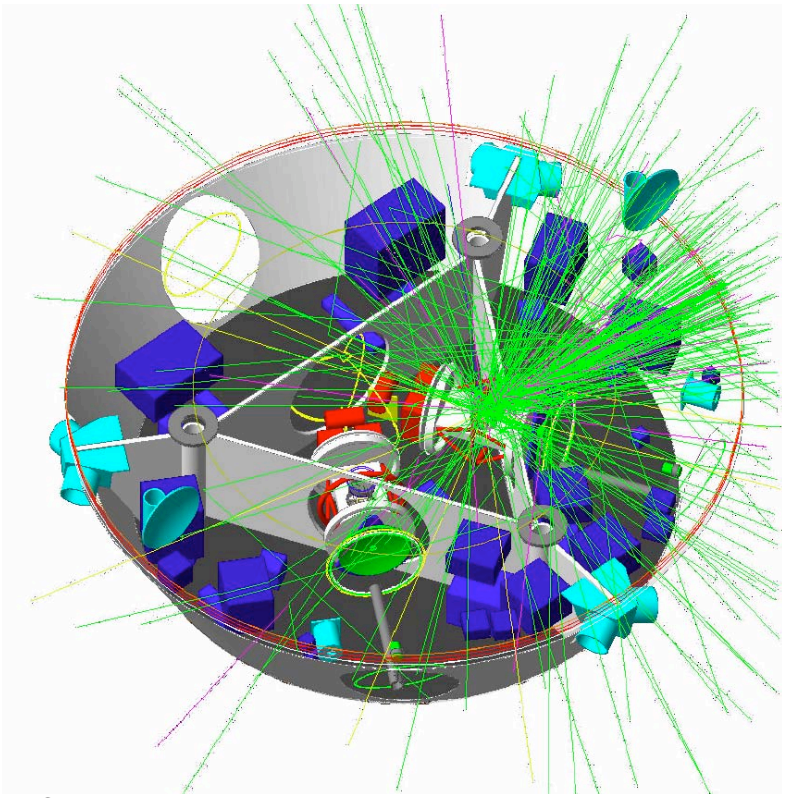


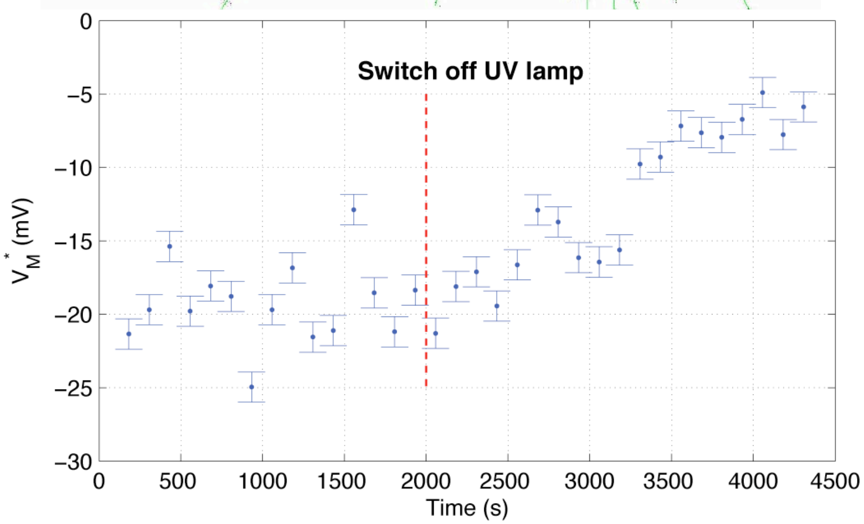


Trento Voltage Compensation Demonstration

Proof Mass Charge

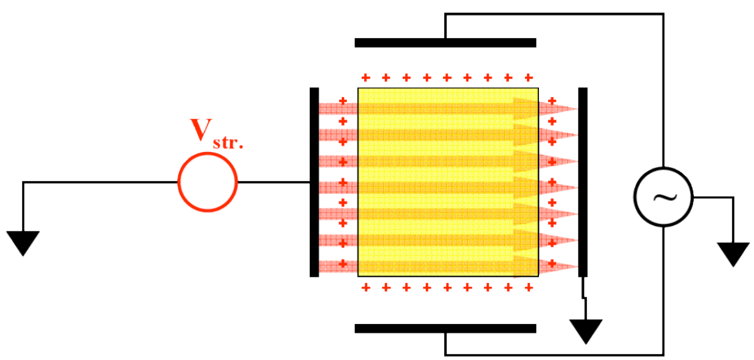
- Cosmic ray impacts will charge the PM.
- Total charge and charge fluctuations will couple to the DC field causing spurious accelerations.
- Charge fluctuations are ∝to the charging rate:
  - Imperial College GEANT4 model predicts charging rate of < 50 e/s.
  - INFN Fluka model predicts charging rate of 150 e/s.
  - Charging rate on GP-B was 8 e/s (Imperial College predicted 12.5 e/s GEANT4).
- Total charge controlled by shining UV light on PM and housing.
  - Measurements at Trento demonstrate charge reduction to ~5x10^{6}e (2x lower than budget).



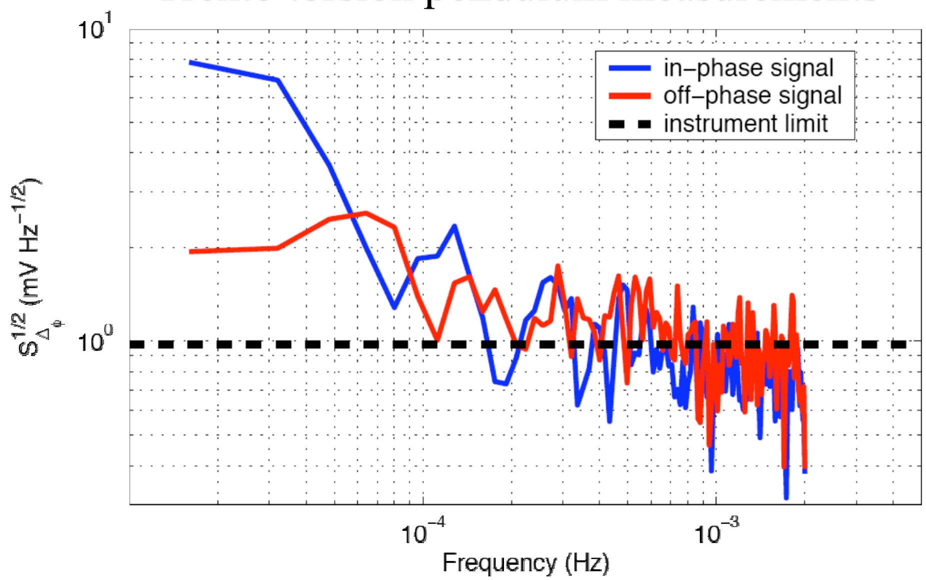


Voltage Fluctuations

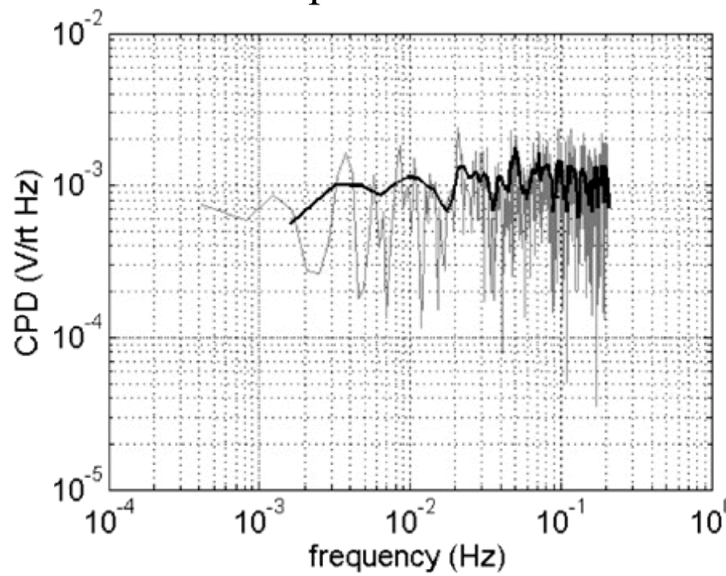
- DC field will fluctuate due to:
  - Changing patch fields,
  - Noise in applied voltages.
- Voltage fluctuations will couple to PM charge and stray DC potential:
  - Measurements at Trento put upper limit at ~1 mV/√Hz at 0.1mHz, ~100x budget value.
  - Measurements on GSFC Kelvin probe put upper limit at ~1 mV/√Hz at 0.4mHz.



Trento torsion pendulum measurements

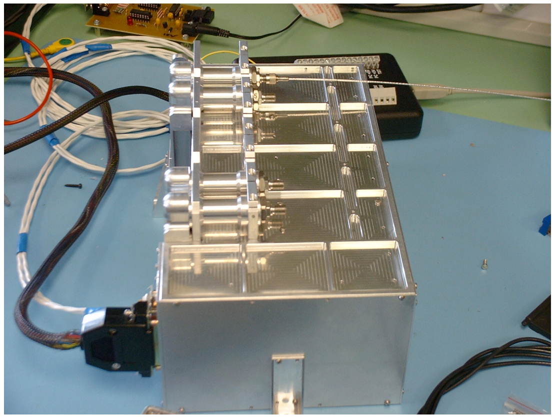


GSFC Kelvin probe measurements

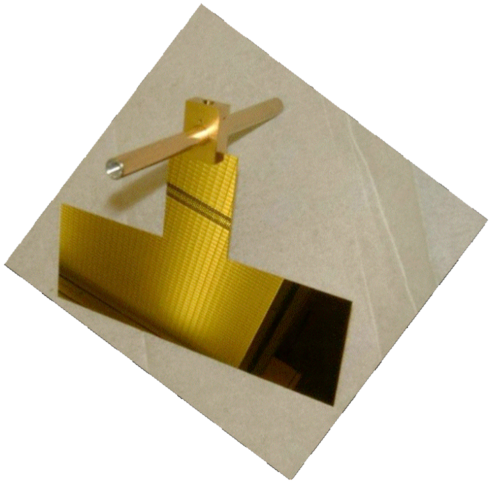


Achieving Charge & Voltage Performance

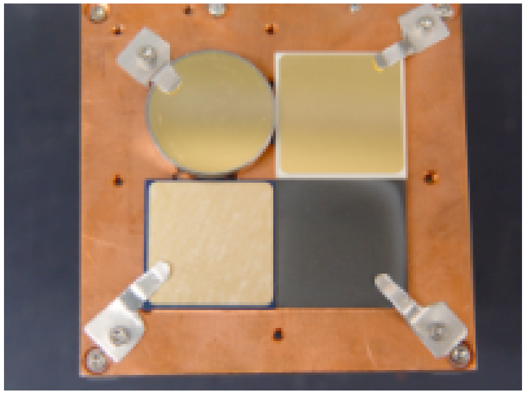
- Wide gap between PM and housing,
- No applied DC voltages along sensitive axis,
- Stray DC voltage active compensation,
- High quality surface coatings,
- High stability power supplies,
- Continuous UV discharging of proof mass.



LTP UV Lamp

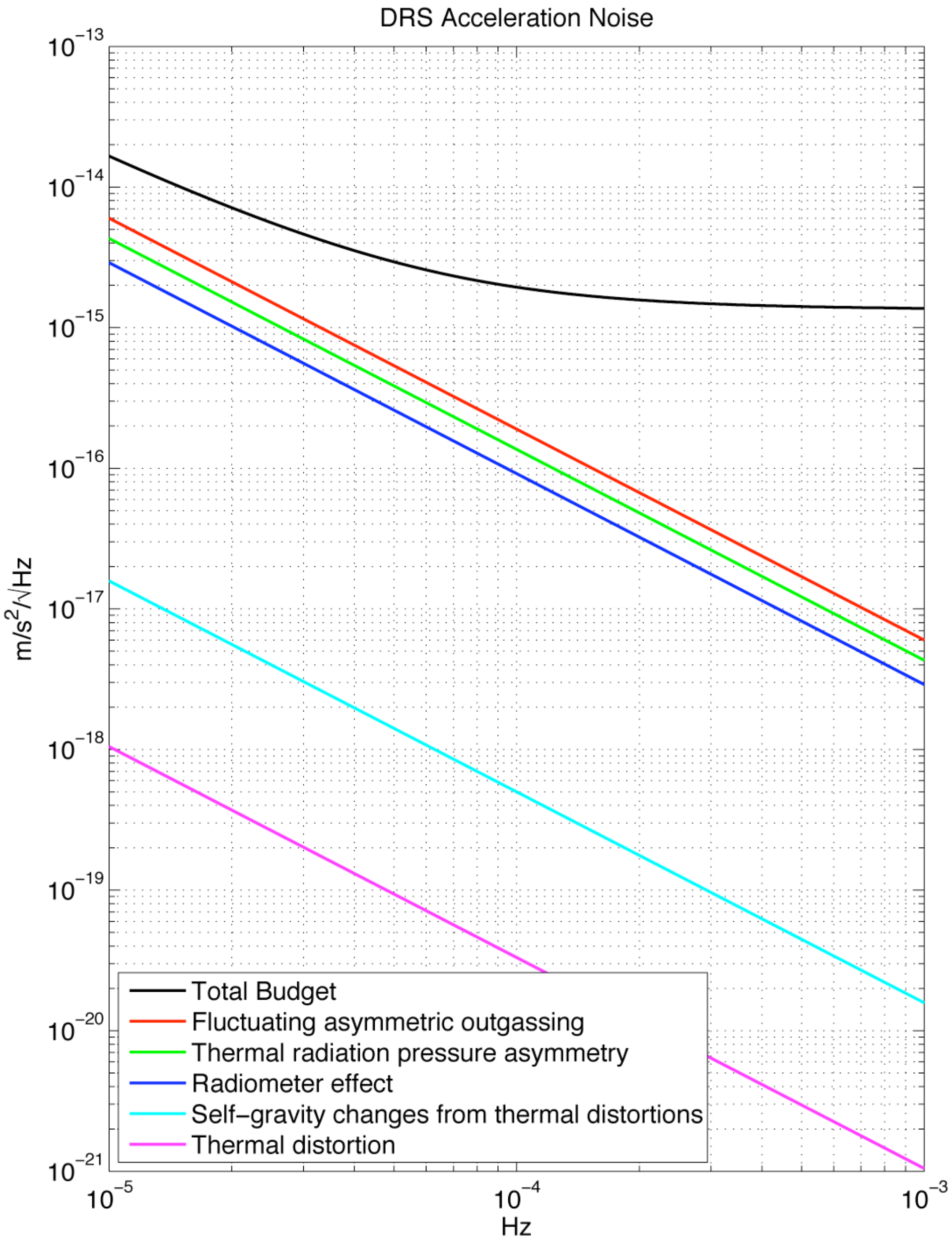


UW Small Force Pendulum

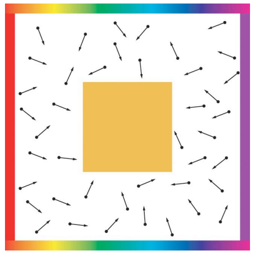


Material samples for Kelvin probe

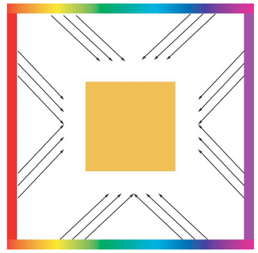
Thermal Effects



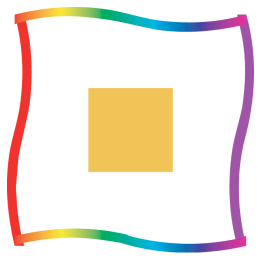
- Fluctuating asymmetric outgassing
  - Fluctuating pressure due to temperature dependent outgassing



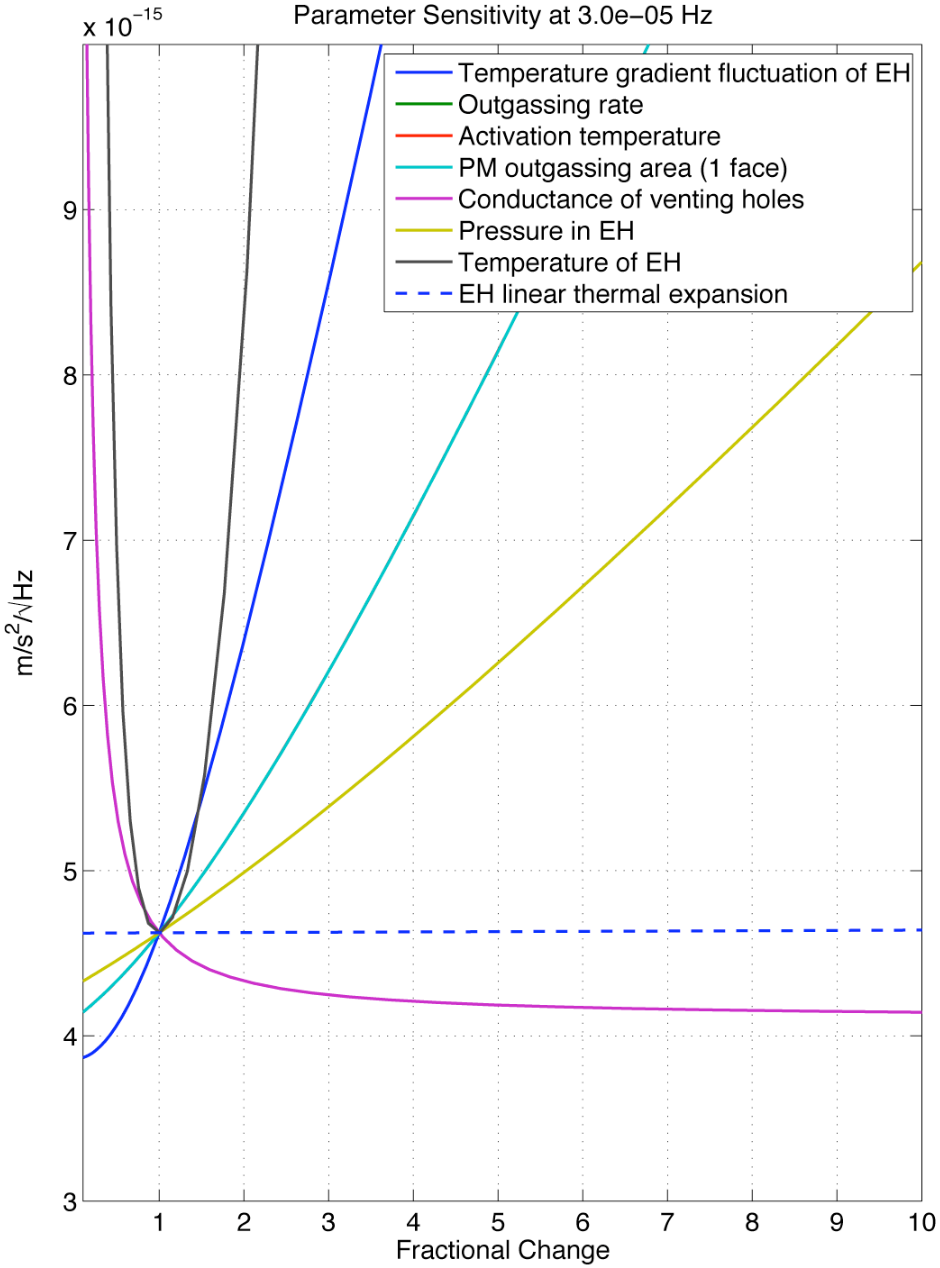
- Radiometer effect
  - Fluctuating temperature gradient of residual gas



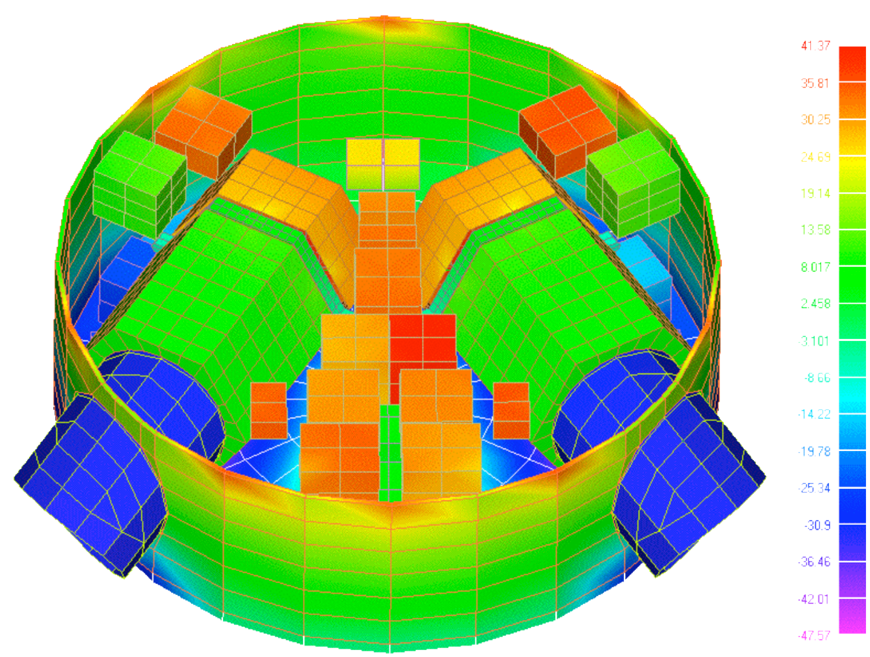
- Thermal radiation pressure asymmetry
  - Fluctuating blackbody radiation from EH
- Thermal distortion
  - Housing distortion that couple to PM through self-gravity and capacitance changes.



Thermal Parameters

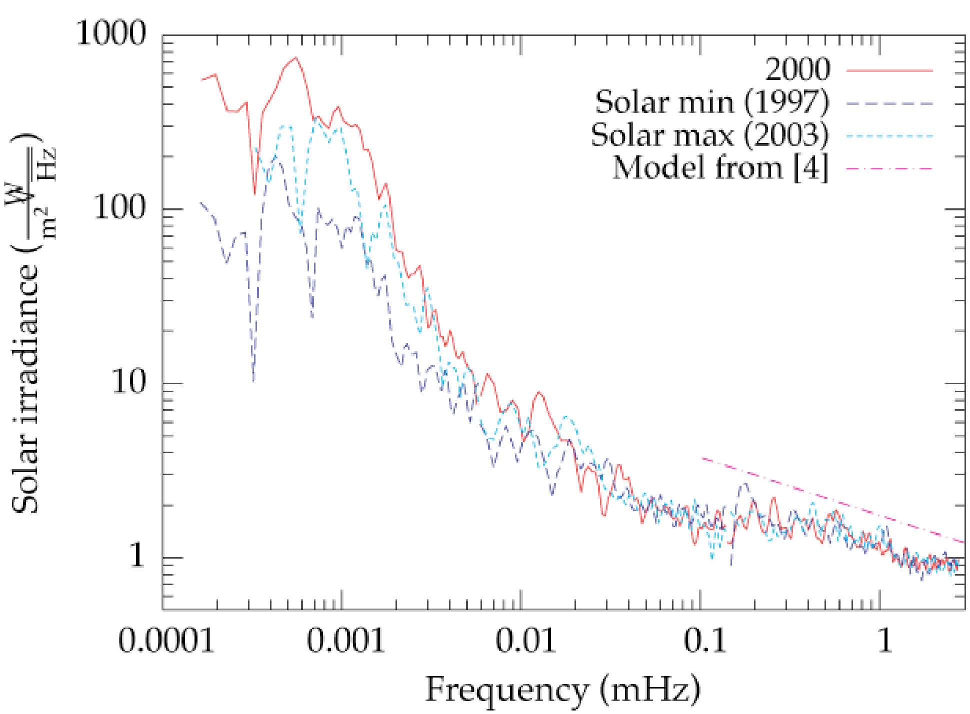


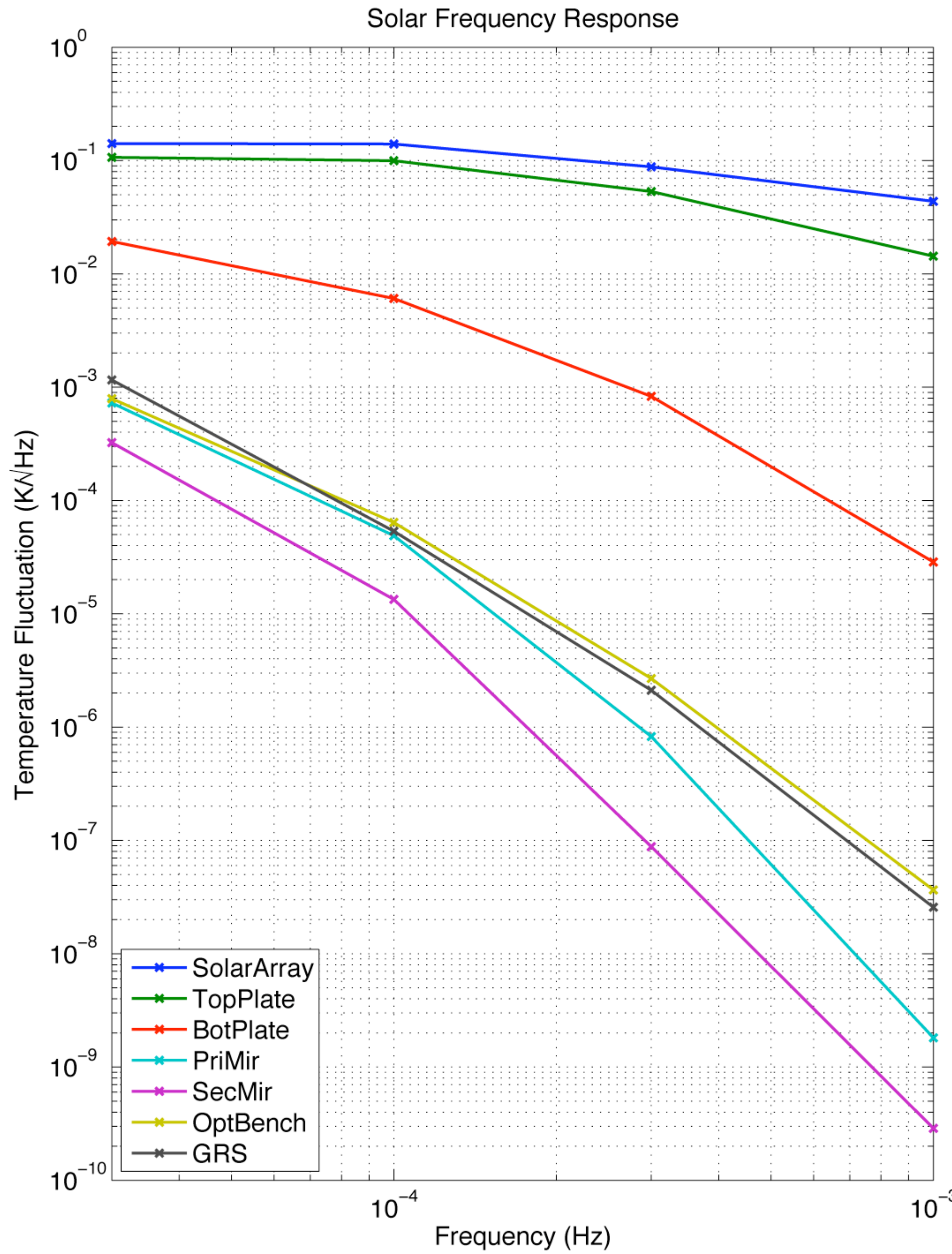
Description	Budget	Units	Sensitivity
Temperature gradient fluctuation of EH	6.1×10^{-5}	K/√Hz	0.304
Outgassing rate	5.0×10^{-7}	kg/s^3	0.138
Activation temperature	3.0×10^{4}	K	0.138
Conductance of venting holes	4.3×10^{-3}	m^3/s	0.138
Pressure in EH	1.0×10^{-5}	Pa	0.075
Temperature of EH	293	K	0.014
EH linear thermal expansion	5.0×10^{-6}	1/K	0.000



Thermal Stability

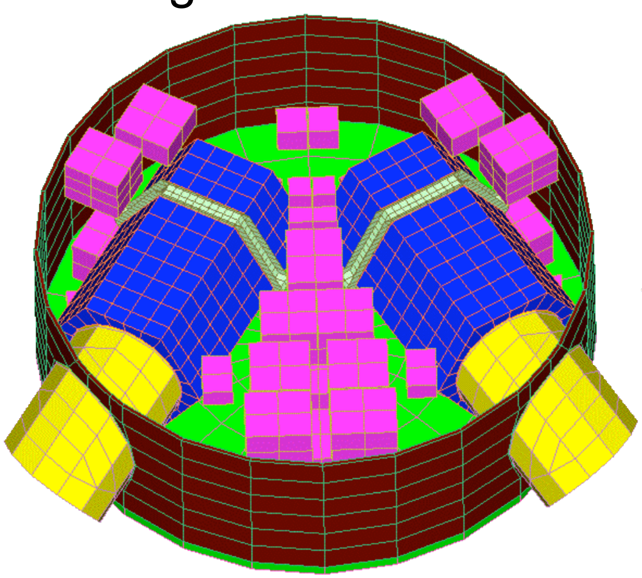
- Thermal fluctuations come from solar input and electronics.
- Current S/C design has several layers of thermal isolation.
- Thermal modeling indicate 10 μK/√Hz at 0.1 mHz gradient feasible at GRS.

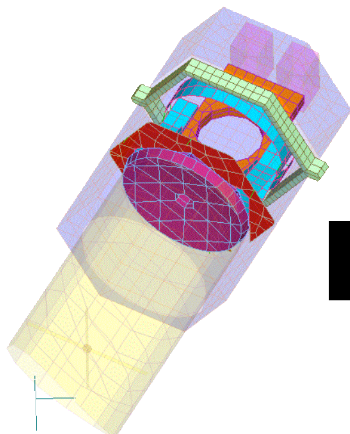


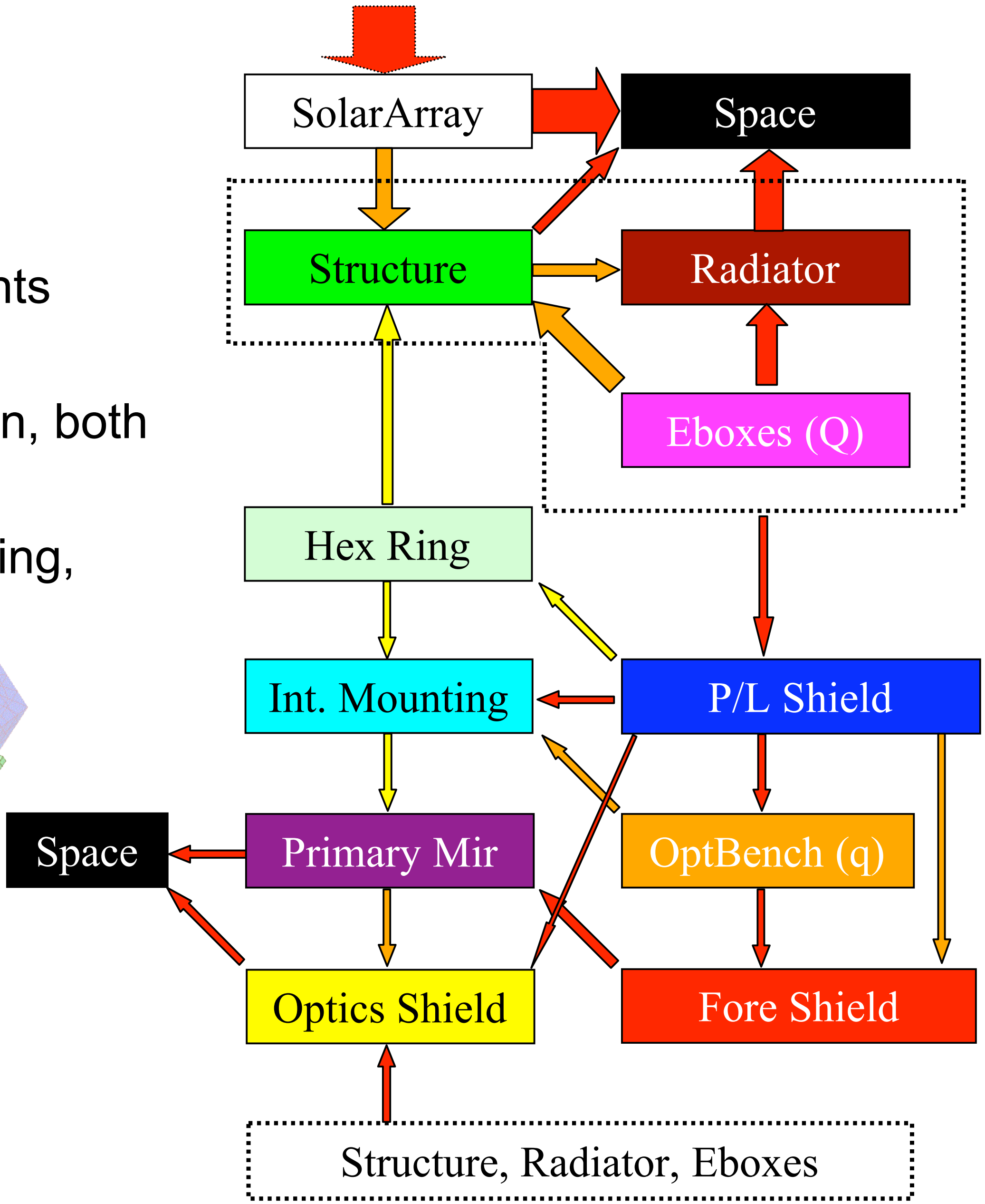


Achieving Thermal Performance

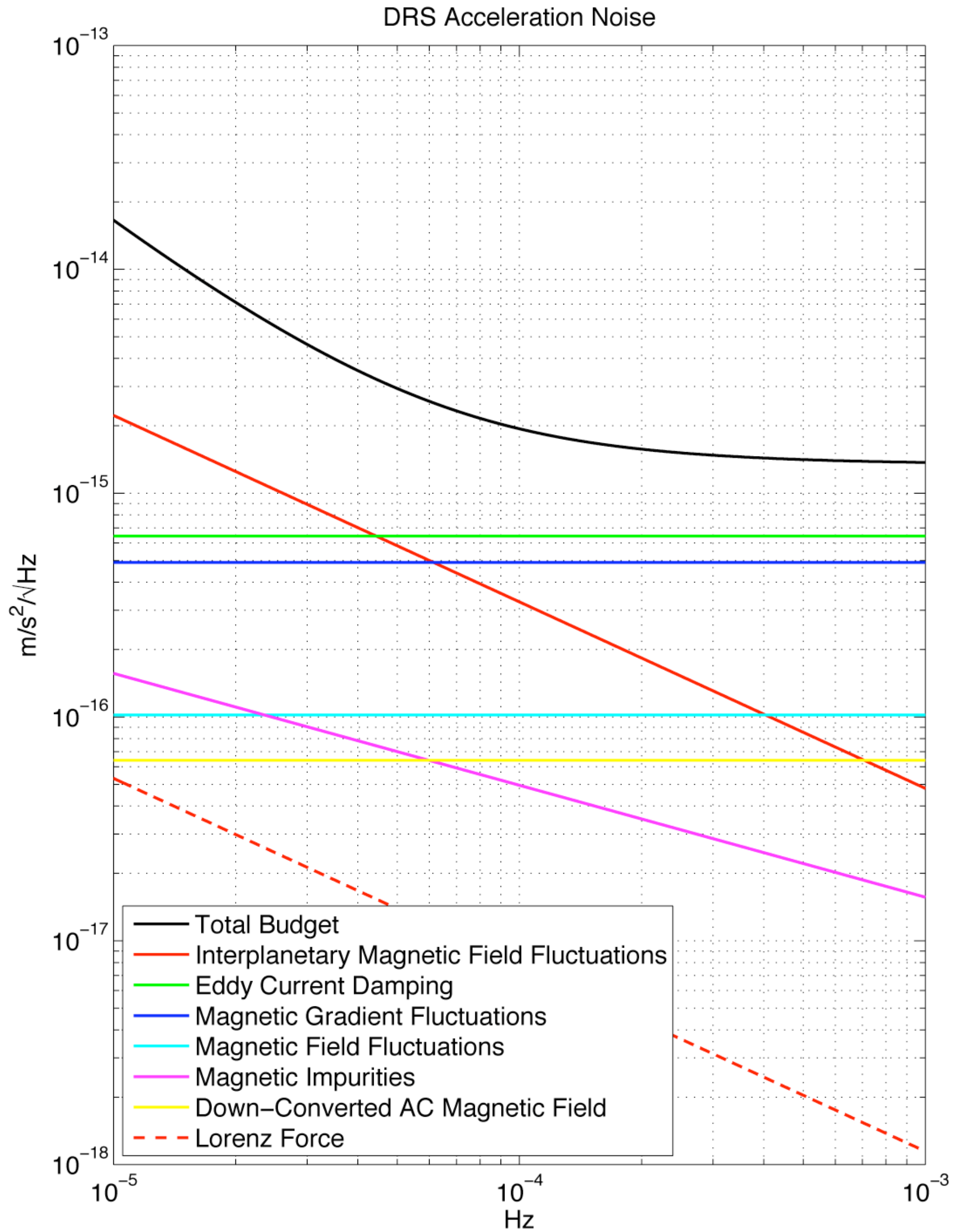
- Thermally stable environment
  - Constant orientation to sun,
  - Zero Earth/Albedo
- Power Stabilized electrical components (constant dissipation),
- Descending layers of thermal isolation, both conductive and radiative,
- Thermally conductive electrode housing,
- High vacuum.





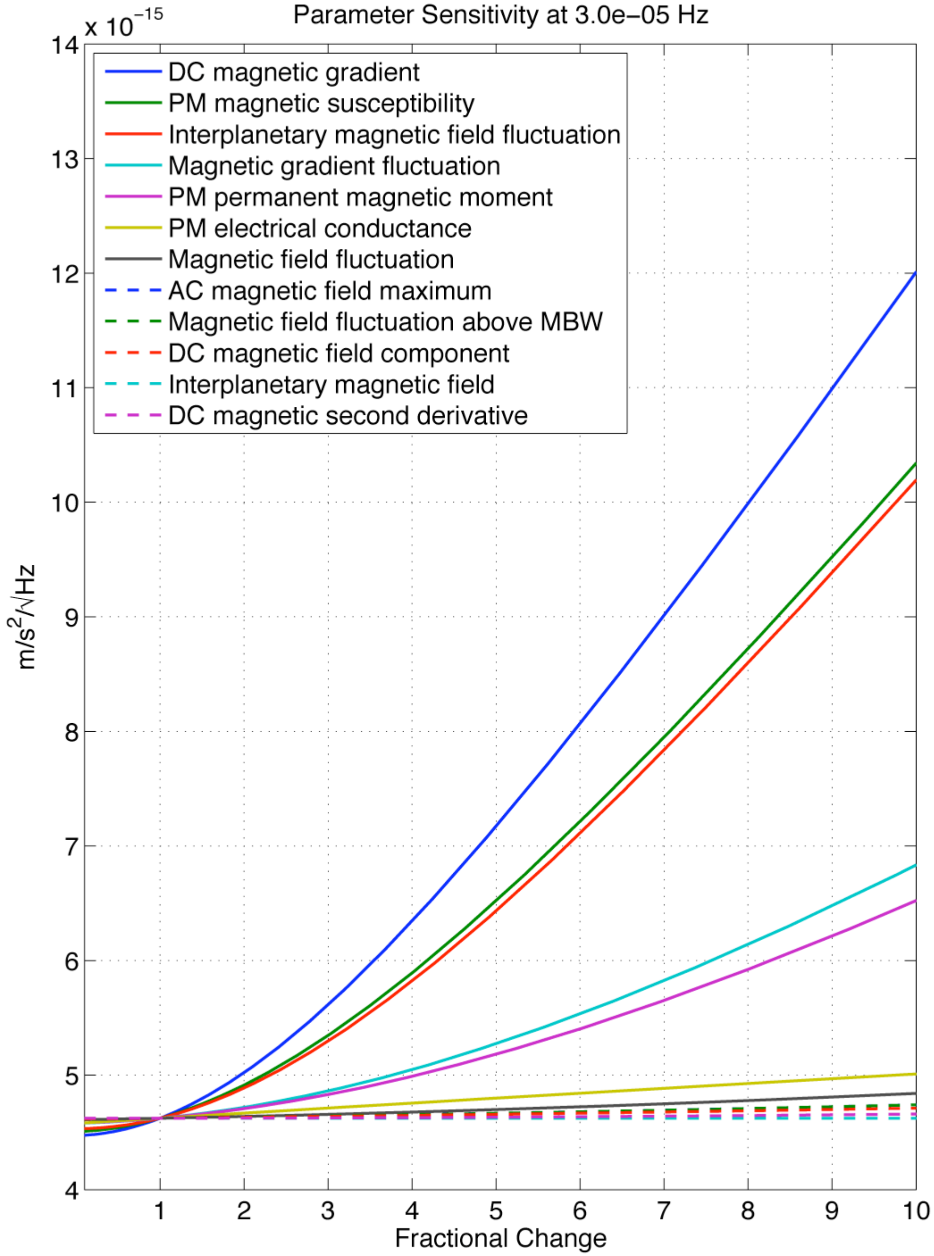


Magnetic Effects

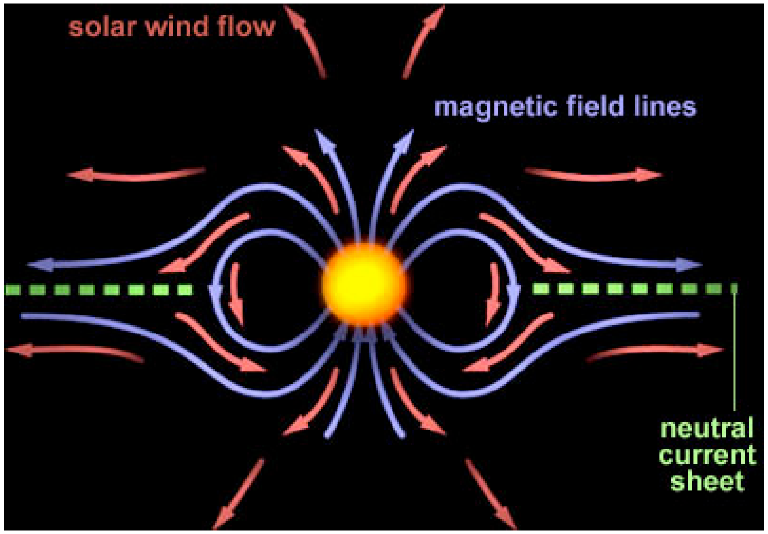


- Interplanetary magnetic field fluctuations:
  - Interaction between IP magnetic field with S/C magnetic gradient and PM magnetic susceptibility.
- Eddy current damping:
  - Fluctuations from magnetic gradient induced current dissipations.
- Magnetic gradient fluctuations:
  - Interaction between fluctuating S/C magnetic gradient and PM magnetic susceptibility and residual dipole moment.

Magnetic Parameters



Description	Budget	Units	Sensitivity
DC magnetic gradient	5.0×10^{-6}	T/m	0.061
PM magnetic susceptibility	3.0×10^{-6}		0.045
Interplanetary magnetic field fluctuation	8.7×10^{-7}	T/√Hz	0.039
Magnetic gradient fluctuation	2.5×10^{-8}	T/m/√Hz	0.015
PM permanent magnetic moment	2.0×10^{-8}	A m^2	0.014
PM electrical conductance	5.0×10^{-8}	A/V/m	0.010
Magnetic field fluctuation	1.0×10^{-7}	T/√Hz	0.003
AC magnetic field maximum	5.0×10^{-7}	T	0.002
Magnetic field fluctuation above MBW	1.0×10^{-8}	T/√Hz	0.002
DC magnetic field component	1.0×10^{-5}	T	0.002
Shielding factor	1.0×10^{-3}		0.001
Interplanetary magnetic field	3.0×10^{-8}	T	0.000
DC magnetic second derivative	2.0×10^{-1}	T/m^2	0.000



S/C Magnetic Field

- Levels required by LISA are more than 10x easier than magnetically clean spacecraft.
- Magnetic gradients come mostly from:
  - Strong magnetic materials
  - Soft magnetic materials
  - Currents
- Magnetic zones can be set up to take advantage of r^4.

$$\mu = \frac{2\pi}{3\mu_0} r^4 \max\left(B_{xx}\right)$$

- $B_{xx}=1\times10^{-6}$ T/m is equivalent to 20 J/T dipole 1.86 m away.
- Current watch list meets requirements with modest shielding.

Component	Quantity	Dipole (J/T)
HGA Drive Mechanism	2	
Transponders	2	
RFDU	1	
Heaters	Many	
Solar Array	1	
Battery (9A/h LiIon)	1	
Power System Electronics	1	
Power Switching & Distribution Unit (PSDU)	1	
SSPA/TWTA	2	15
Lasers	4	
Isolator	4	10

Magnet Watch List

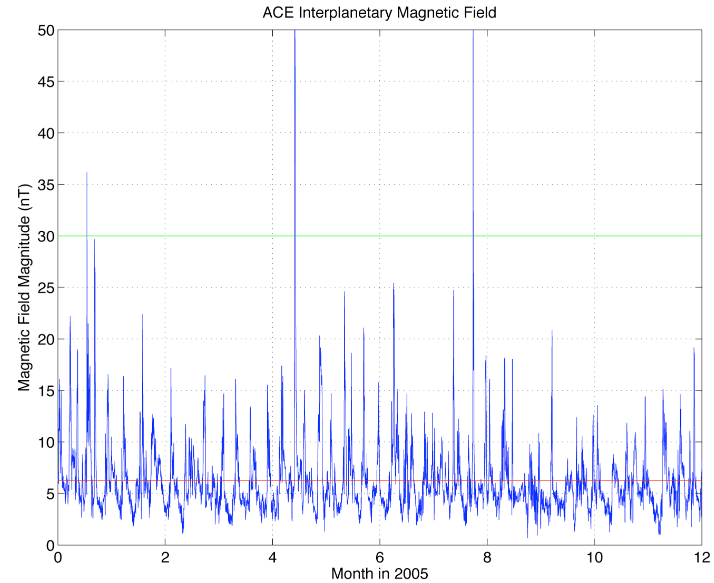
Zone	Name	Min PM Distance	Max Magnetic Dipole (A-m^2)
A	Proof masses	0	0
B	Proof mass housings	2	2.70E-12
C	Optical bench	44	6.20E-07
D	Telescope assembly	222	4.00E-04
E	Y-tube outer surface	225	4.30E-04
F	Outside the Y-tube, beyond 250 mm	250	6.50E-04
G	Outside the Y-tube, beyond 500 mm	500	1.00E-02
H	High Gain Antennas	936	1.30E-01
I	Solar array	200	2.70E-04

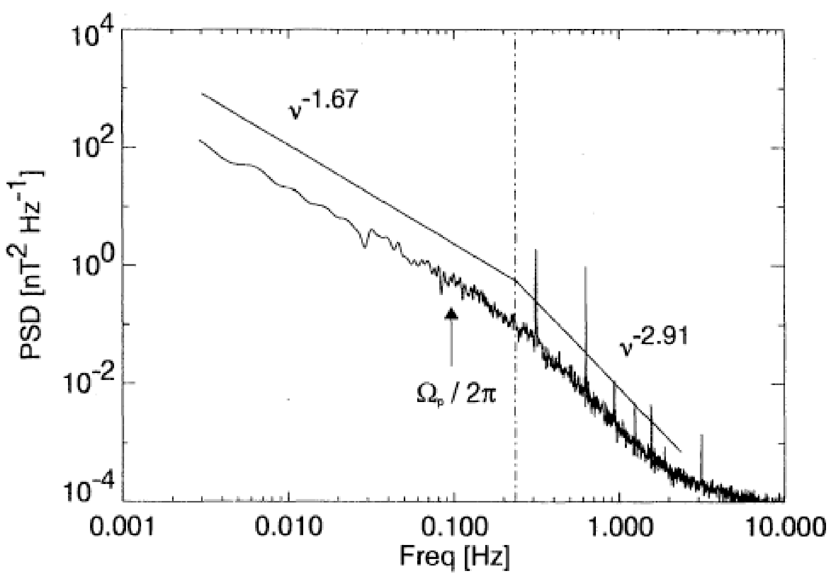
Magnetic Zones

Interplanetary Magnetic Field

- Good data exists on interplanetary magnetic field from ACE, Cluster, and other S/C.
- 2005 ACE MAG data has a mean of 6.3 ± 3.7 nT. The value currently assumed in the error budget is 30 nT, more than 6σ higher.
- The spectral behavior matches well classical Kolmogorov fluid turbulence, thus the power spectral density of the fluctuations will have an $f^{-5/3}$ behavior.
- Magnitude of the power spectrum varies considerably. Conservatively assume 320 nT/√Hz at 0.1 mHz.

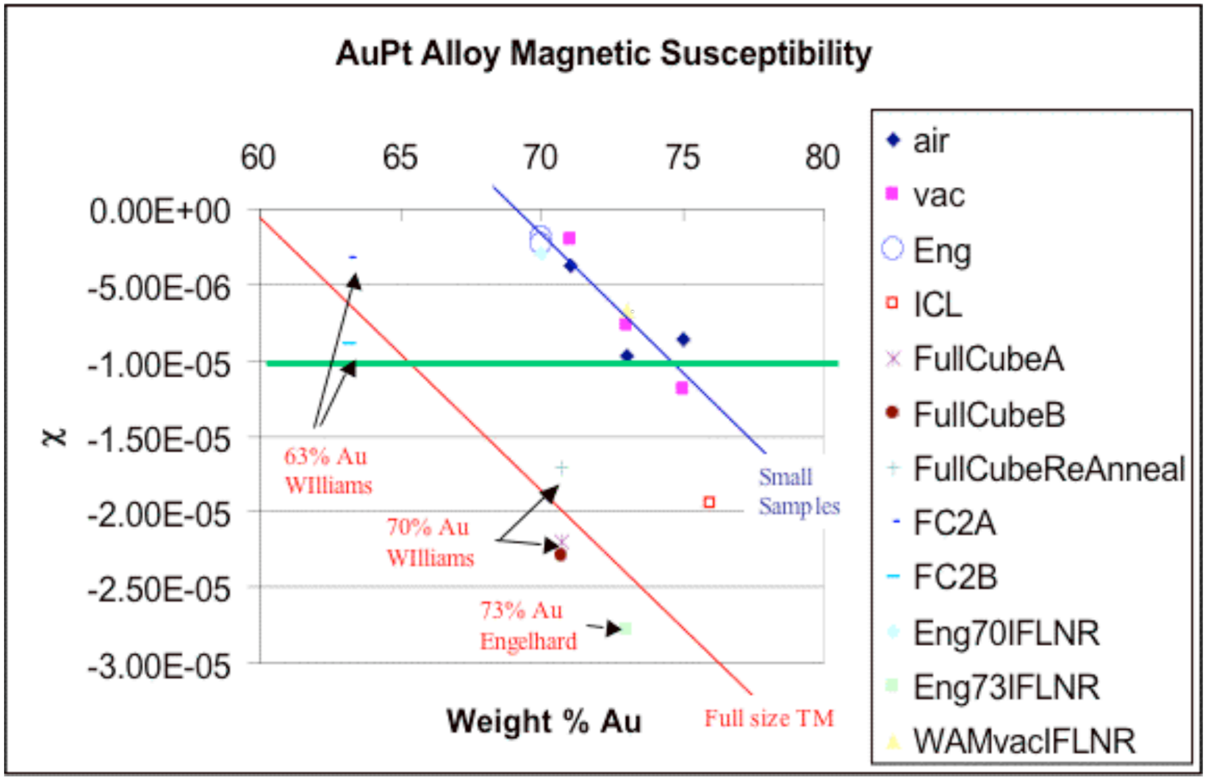
$$\sqrt{S_{Bi}} = 320nT/\sqrt{Hz}\sqrt{\left(\frac{10^{-4}Hz}{f}\right)^{5/3}\frac{1}{1+\left(\frac{f}{0.44Hz}\right)^{3}}}$$



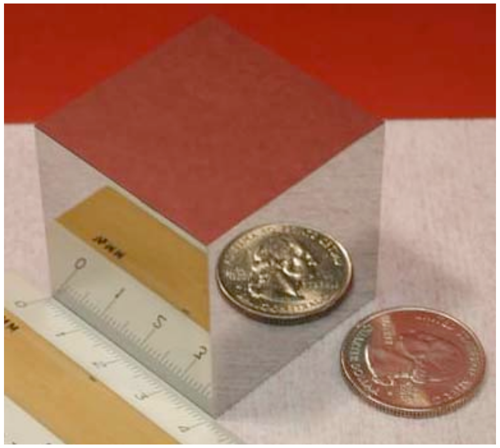


R. Leamon *et al.*, J. Geophys. Res. **104**, 22331 (1999).

Proof Mass Magnetic Properties

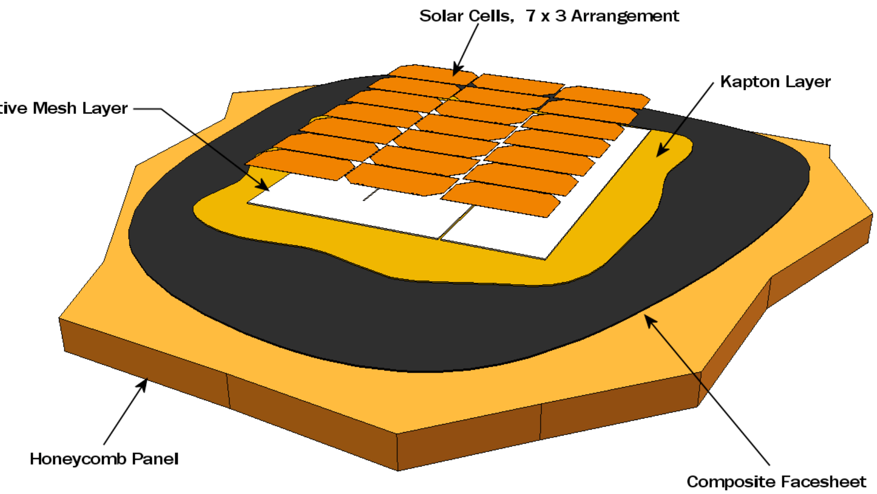


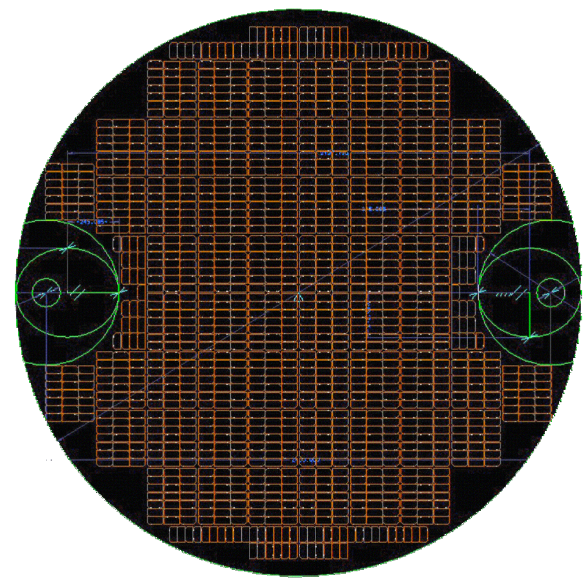
- From Stanford measurements we find that a magnetic susceptibility of _=1.7x10^{-5} is achievable in a full scale PM.
  - 3x10^{-6} previously assumed in the error budget.
- Full sized sample had a magnetic moment of ≤ 12 nA m^2.
  - 20 nA m^2 assumed in the error budget.



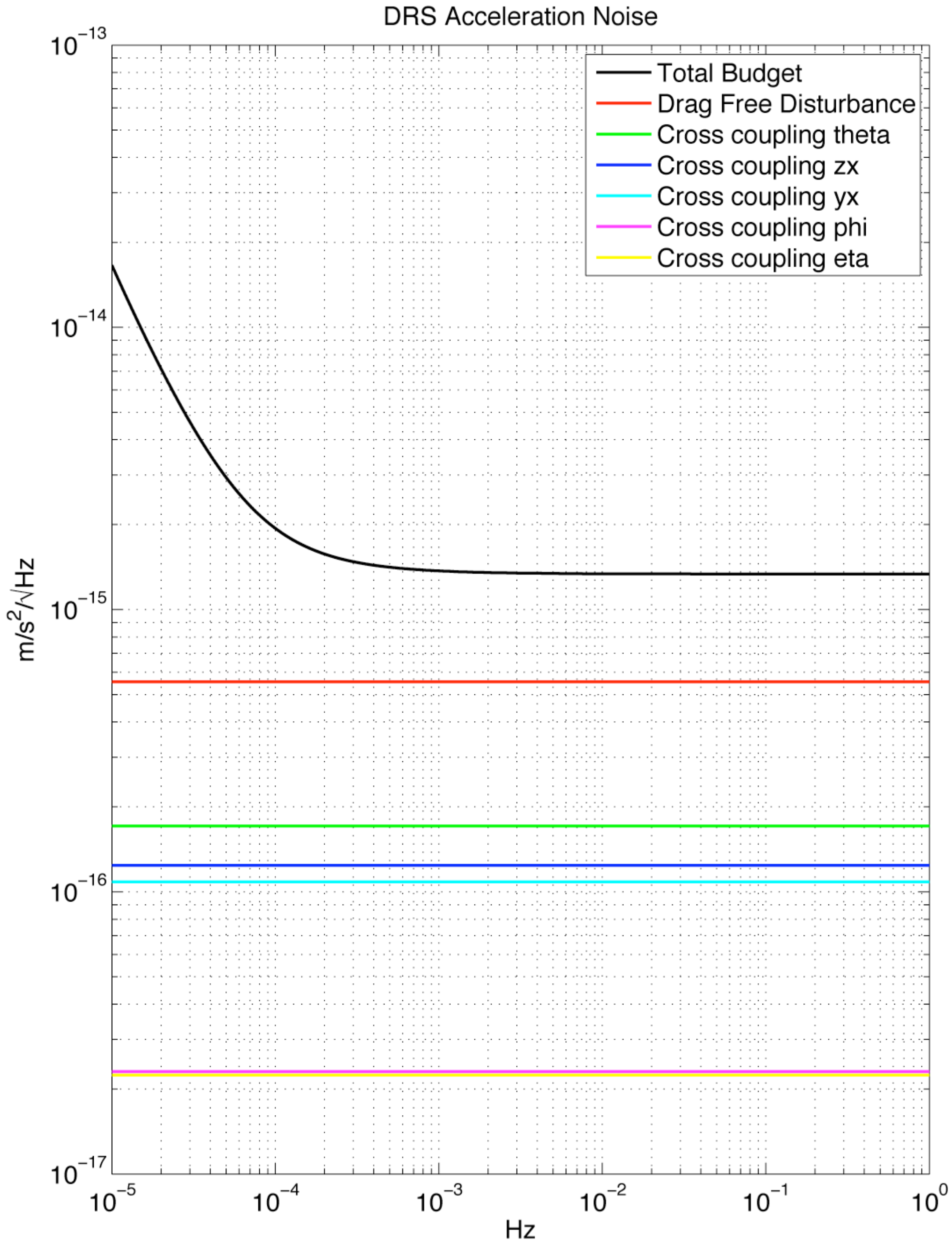
Achieving Magnetic Performance

- Minimize PM magnetic properties.
- Minimize use of magnetic material.
- Permanent magnets can be compensated with oppositely oriented duplicate such as the cold spare.
- Remaining permanent magnets can be shielded with METGLAS (Metglas Solutions, Inc) or VITROVAC (Vacuumschmeltze).
- Backwire solar array.
- Use twisted pair for all wiring.
- Eliminate current loops in power system using star or single point grounding.
- No primary supply currents should be allowed to flow through the spacecraft structure.
- Small thermal gradients.





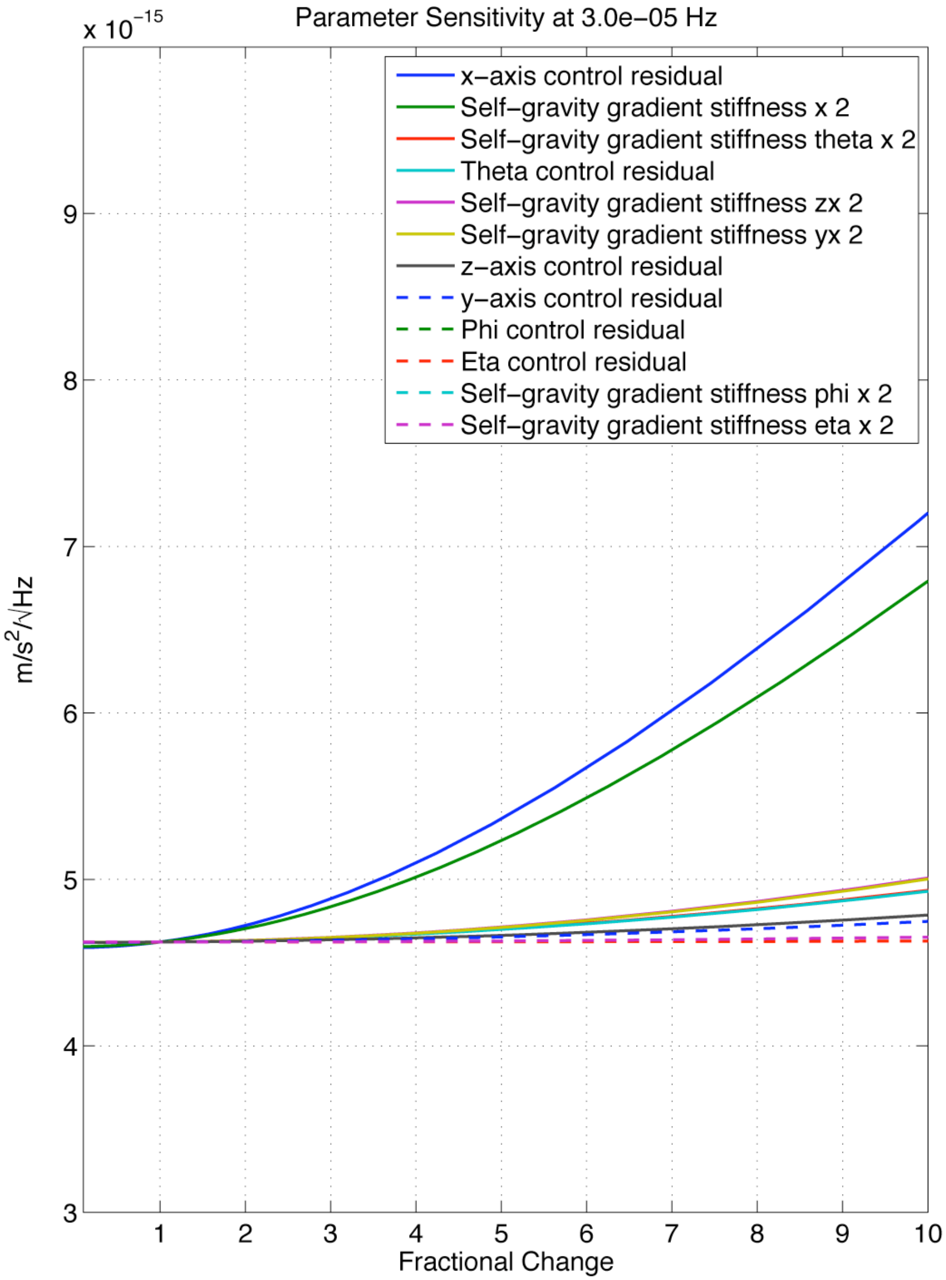
Spacecraft - PM Coupling



- Residual S/C motion will couple to PM through stiffness.
- Off-diagonal stiffness terms will cross-couple S/C motion to sensitive axis.
- Self-gravity gradient dominates stiffness budget.

Description	Budget (s^{-2})
Self-Gravity Gradient	1.00E-07
Sensing Stiffness	4.34E-08
Rotation Actuation Stiffness	1.64E-08
Magnetic Stiffness	1.18E-08
DC Voltage Stiffness	3.59E-09

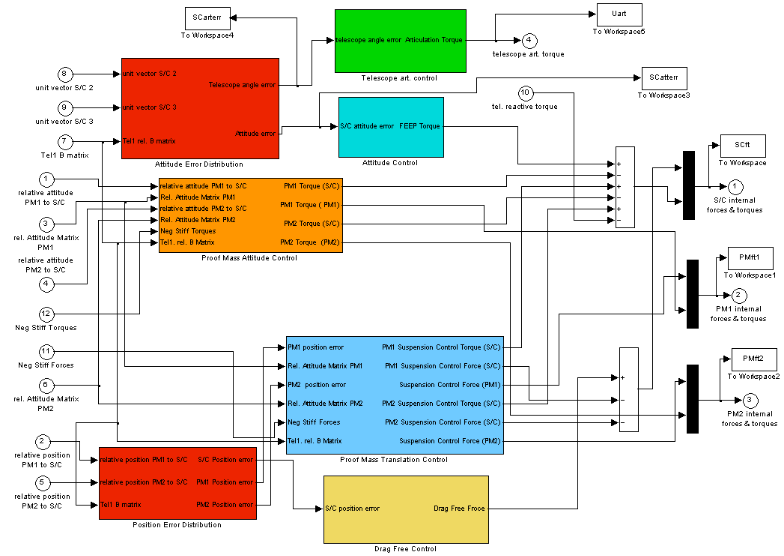
Spacecraft - PM Coupling Parameters

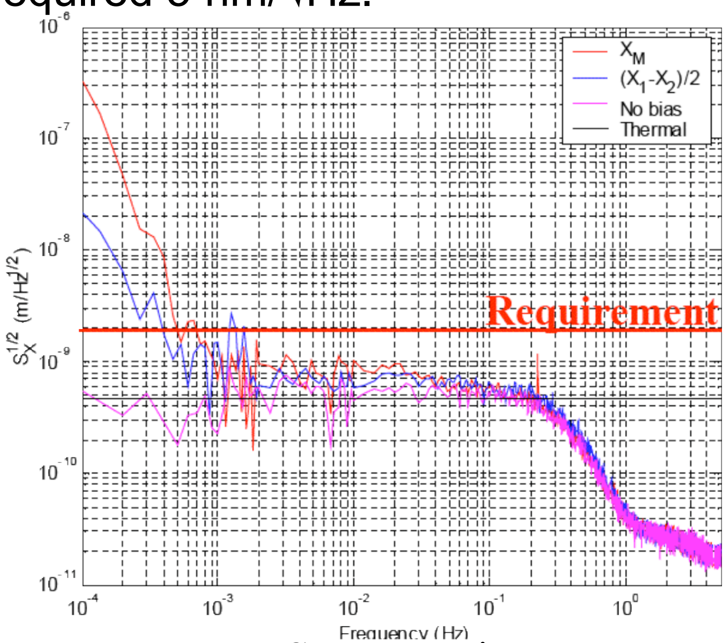


Description	Budget	Units	Sensitivity
x-axis control residual	5E-09	m/√Hz	0.014
Self-gravity gradient stiffness x	1E-07	s^{-2}	0.012
Self-gravity gradient stiffness theta x	5E-08	s^{-2}	0.001
theta control residual	2E-07	rad/√Hz	0.001
Self-gravity gradient stiffness zx	2E-08	s^{-2}	0.001
Self-gravity gradient stiffness yx	2E-08	s^{-2}	0.001
z-axis control residual	1E-08	m/√Hz	0.001
y-axis control residual	1E-08	m/√Hz	0.001
Self-gravity gradient stiffness phi x	5E-08	s^{-2}	0.000
Self-gravity gradient stiffness eta x	5E-08	s^{-2}	0.000
phi control residual	5E-08	rad/√Hz	0.000
eta control residual	5E-08	rad/√Hz	0.000

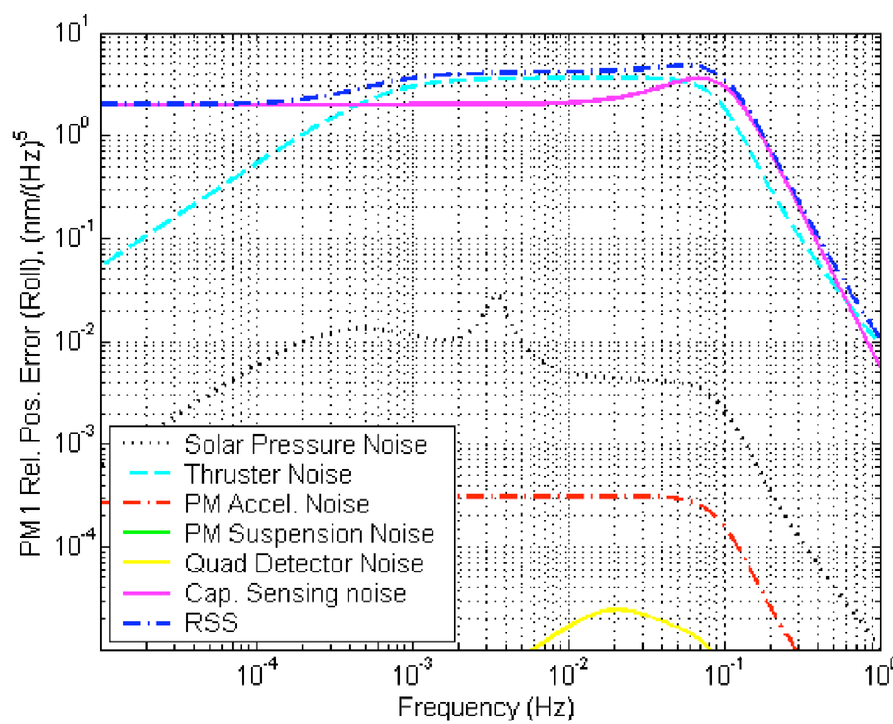
Control Law Performance

- Full LISA DRS model: S/C (6-DOF), two Proof Masses (6-DOF each), and telescope articulation for total of 19_DOF.
- Three S/C combined gives 57-DOF.
- Nonlinear translational and rotational kinematics and dynamics.
- Preliminary designs completed for all DRS control systems.
- Control is straightforward and simulations predicts position control better than required 5 nm/√Hz.

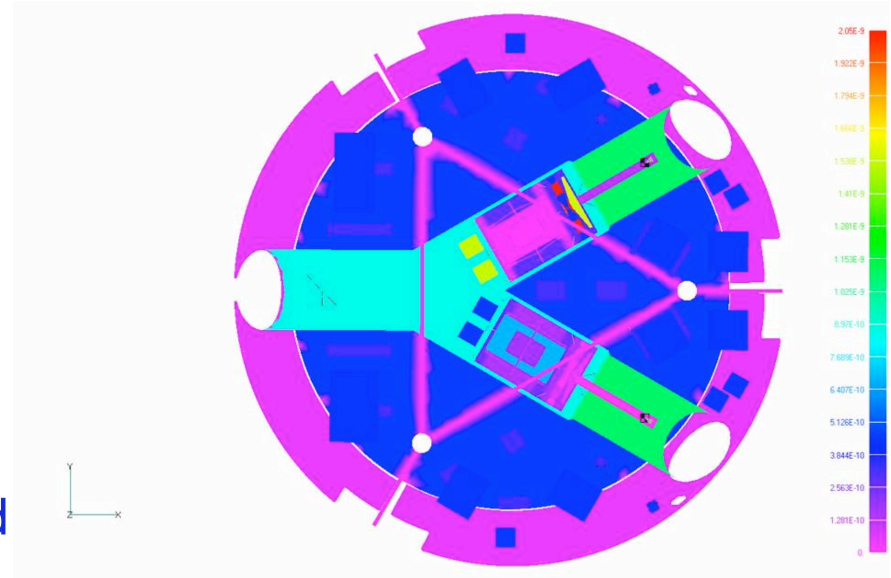


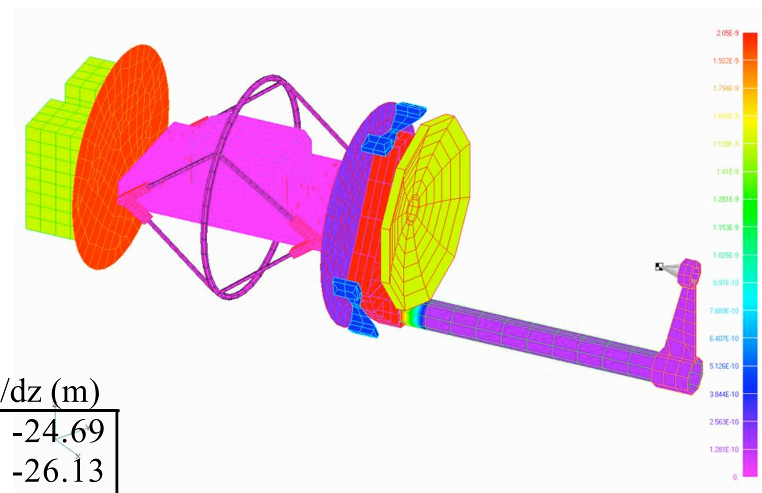


LTP Prototype Sensor Noise Measurements



Self-Gravity Gradient



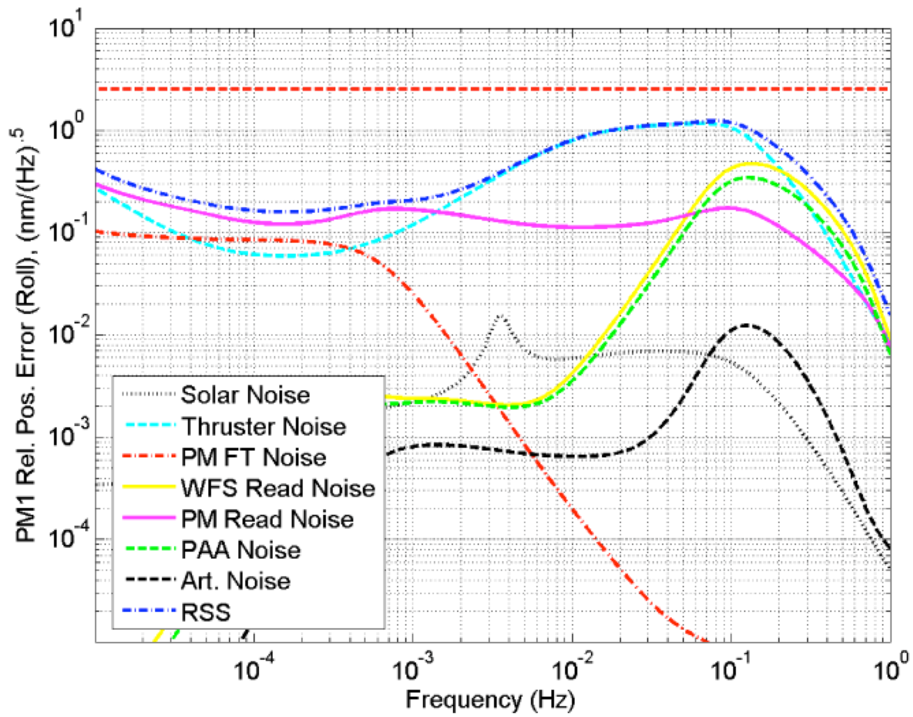


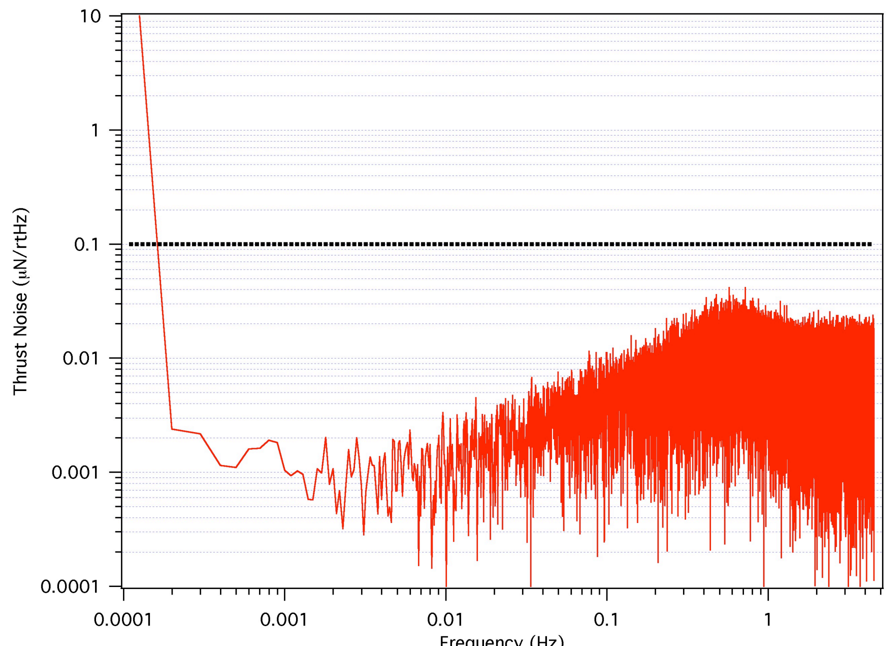
- Self-gravity gradient is the dominant stiffness term.
- Self-gravity tool developed to aid in design and verification.
  - Computes forces, moments, and gradients on each proof mass,
  - Tools accept distorted and undistorted cases
  - Visualization capability to map contributions.
- Analysis of unoptimized design within 4x of budget.

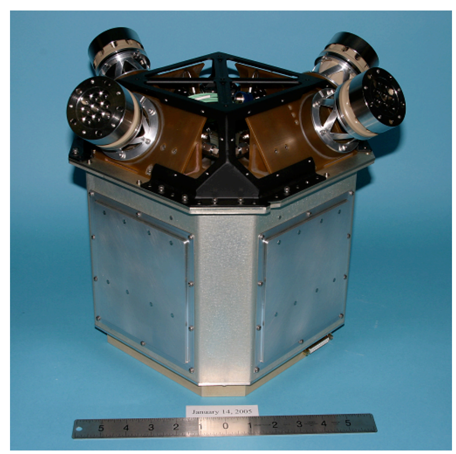
		/dx (m)	/dy (m)	/dz (m)	/dx (m)	/dy (m)	/dz (m)
dAx $(1/s^2 \times 10^{-10})$	=	-1264.32	85.39	-25.74	-1258.04	-104.25	-24.69
dAy $(1/s^2 \times 10^{-10})$	=	85.39	1669.91	7.20	-104.25	1666.05	-26.13
dAz $(1/s^2 \times 10^{-10})$	=	-25.74	7.19	-405.60	-24.69	-26.13	-408.01
$d\alpha x$ $(r/s^2/m \times 10^{-10})$	=	1.81	1137.84	49.92	1.42	1138.13	50.69
$d\alpha y$ $(r/s^2/m \times 10^{-10})$	=	-300.77	-0.70	-9.01	-300.88	-0.45	-6.62
$d\alpha z$ $(r/s^2/m \times 10^{-10})$	=	-1.73	-8.19	-1.11	-0.16	-4.63	-0.97

Achieving Spacecraft - PM Coupling Performance

- Improve sensor sensitivity
  - Simulation using optical sensing predicts position control of 0.18 nm/√Hz @ 0.1 mHz (more than 10x better than budget).
- Use low-noise thrusters
- Careful tracking of all sciencecraft mass.







Summary

- The very low end of the LISA frequency band has the potential for exciting science.
- Pushing the low-frequency sensitivity will increase the precision of locating a source on the sky for follow-up observations.
  - LISA will measure the absolute distance and an electromagnetic identification of the source measures the redshift enabling us to map dark energy very far back in time with almost no interpretation problems.
- Many design options are available to improve low-frequency performance.
- Greatest challenge at low-frequency is verification of performance on-ground. Reliance on modeling may be heavy.